PHYSIOLOGICAL DEMANDS OF COMPETITIVE TAEKWONDO

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ABSTRACT

Taekwondo has evolved from a traditional martial art into a modern-day Olympic combat sport. Despite this transition, knowledge of the physiological demands of this combat sport is in its infancy. This thesis investigates the physiological demands of competitive Taekwondo using experienced male international Taekwondo competitors.

Physiological measures and activity profile information were initially collected in championship Taekwondo competition to determine the fundamental physiological demands of this combat sport. The activity profile of championship Taekwondo combat elicited near-maximal heart rate (HR) responses and high blood lactate concentrations. The activity levels and physiological responses (e.g. HR and blood lactate) increased significantly between round 1 and 3 of combat. These data collectively suggest that the activity pattern of Taekwondo combat imposes high aerobic and anaerobic demands on the competitors, and these energetic requirements are increased as the rounds progress. The activity profile in championship combat was also modulated by a competitor's weight division. Most notably, the data highlighted a predominance of fighting activity for heavy weights, and longer preparatory actions and less frequent fighting exchanges for feather weights.

A Taekwondo competition simulation was devised and implemented to examine the physiological and hormonal responses to Taekwondo combat in simulated and championship settings. The championship Taekwondo combats elevated the physiological (e.g. HR, plasma lactate, glucose and glycerol) and hormonal responses (e.g. plasma adrenaline and noradrenaline) in comparison to simulated combats performed in a controlled setting. These divergent responses were evident even though both combat settings exhibited comparable activity profiles. This suggests that the contrasting physiological and hormonal responses were mediated by the stress responses to fighting in championship events.

The physiological and hormonal responses to performing successive Taekwondo combats were examined during a simulated championship event. Performing four combats in an ecologically valid competition time-structure modulated the physiological and hormonal responses to combat and perturbed homeostasis between the combats. Most notably, the successive combats resulted in reduced plasma noradrenaline and lactate responses to combat and increased HR responses earlier in combat. These responses may reflect a change in the activity of the competitors' and/or altered metabolic function in favour of an increased reliance on aerobic metabolism and diminished anaerobic energy yield as the combats are repeated. Importantly, the HR and plasma concentrations

of glycerol, NEFA and lactate remained elevated above baseline levels between a number of the repeated combats. This suggests that the recovery processes were often incomplete between the combats.

The collective findings of these investigations demonstrate that Taekwondo is an intermittent combat sport that elicits high demands upon both aerobic and anaerobic metabolism. The physiological requirements of Taekwondo combat may be regulated by a multitude of competition factors including a competitor's weight division, the round of combat and performing successive combats with different recovery intervals. Taekwondo combat also activates the sympathetic-adrenal-medulla promoting the release of stress hormones (catecholamines) into the circulation. The stress-hormonal responses are mediated by the specific combat environment and the requirement to perform repeated combats within a single day. These original findings may serve as a valuable ergonomic framework to prepare competitors' for the specific requirements of Taekwondo competition.

Key Words: Taekwondo, combat sport, physiological responses, hormonal responses, activity profile, competition, training, metabolism, physiology, intermittent exercise

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ATP	Adenosine triphosphate
cAMP	Cyclic adenosine monophosphate
CK	Creatine kinase
CMJ	Counter Movement Jump
CO_2	Carbon dioxide
COMT	Catechol-O-methyltransferase
CV	Coefficient of variation (%)
DOPA	3,4-dihydroxyphenyl-alanine
ELISA	Enzyme-linked immunosorbent assay
EPOC	Excess post-exercise oxygen consumption
ES	Effect Size
FSH	Follicle stimulating hormone
GOD-PAP	Glucose oxidase phenol 4-aminoantipyrine peroxidise
GPO-PAP	Glycerol-3-phosphate oxidase phenol 4-Aminoantipyrine-peroxidase
HPA	Hypothalamic-pituitary-adrenocortical axis
HR	Heart rate (Beats.min^{-1})
%HRmax	Heart rate maximum (%)
HSL	Hormone sensitive lipase
IGF-I	Insulin-like growth factor
ITF	International Taekwondo Federation
Kg.bw	Kilograms per body weight
K_2EDTA	Di-potassium ethylenediaminetetraacetic acid
L-AADC	L-aromatic amino acid decarboxylase
LH	Luteinizing hormone
LOA	Limits of Agreement
MET	Metanephrine
NEFA	Non-esterified free fatty acids
NMET	Normetanephrine
PCr	Phosphocreatine
PNMT	Phenylethanolamine N-methyltransferase
RER	Respiratory exchange ratio
RPE	Rating of perceived exertion (Borg's 6-20 scale)
RPM	Revolutions per minute

SAM	Sympathetic-adrenal-medullar
STF	Songaham Taekwondo Federation
TEM	Technical Error of Measurement
V_E	Pulmonary Ventilation ($ml.kg^{-1}.min^{-1}$)
$\dot{V}O_2$	Oxygen uptake ($ml.kg^{-1}min^{-1}$)
$\dot{V}O_{2max}$	Maximum oxygen uptake ($ml.kg^{-1}min^{-1}$)
$\%\dot{V}O_{2max}$	Maximum oxygen uptake (%)
VO_{2peak}	Peak maximum oxygen uptake
W	Watts
$W.kg^{-1}$	Watts per kilogram of body mass
WTF	World Taekwondo Federation
1RM	One-repetition maximum

CHAPTER 1

INTRODUCTION

Taekwondo is a martial art of Korean origin, which in recent years has developed into a modern-day combat sport. Taekwondo competition, governed by the World Taekwondo Federation (WTF), comprises weight-restricted full-contact combat between two opponents. The objective of combat is to overcome an opponent by obtaining either a greater quantity of points for the execution of kicking and punching techniques to permitted scoring areas or by achieving a technical knockout. Taekwondo combats are contested across three two-minute rounds with a one-minute rest interval separating each round. During a championship Taekwondo event, successful competitors are required to compete in qualifying, semi-final and final stage combats within a single day. Taekwondo competition events sanctioned by the WTF are contested at national, regional and international levels, as well as featuring in the official Olympic Games programme (Olympic-Movement, 2010; WTF, 2010).

Despite the emergence of Taekwondo as modern-day Olympic sport, knowledge of the physiological demands of this combat sport is in its infancy. Realisation of the physiological demands of Taekwondo competition and training is necessary to prepare competitors for the specific physiological requirements of international Taekwondo combat (Reilly, Morris & Whyte, 2009). The physiological demands of a sport may be examined by making relevant observations during competition, by obtaining physiological measures during actual and simulated competition, and by determining the physical capabilities of elite competitors (Bangsbo, 1994; Drust, Atkinson & Reilly, 2007). The physical capabilities of elite competitors may provide an insight into the physiological demands of a sport since it may be anticipated that these athletes have adapted to the regular physiological requirements of competition (Bangsbo, 1994). A limited number of investigations have examined the physical capabilities of both recreational and competitive Taekwondo practitioners (Thompson & Vinueza, 1991; Heller *et al.*, 1998; Toskovic, Blessing & Williford, 2004; Markovic, Misigoj-Durakovic & Trninic, 2005; Bouhlel *et al.*, 2006). The available data on the physical capabilities of elite competitive Taekwondo competitors may be associated with the demands of competition, but it may also reflect competitors genetic endowment, health status and the demands of regular training practices as opposed to the less frequent physiological stress of competition (Toskovic *et al.*, 2004; Mohr *et al.*, 2007; Lippi, Longo & Maffulli, 2009). As such, these approaches may not accurately represent the demands of this combat sport.

Collecting physiological measures in an actual championship event would be ecologically favourable to quantify the acute physiological demands of Taekwondo combat. Few investigators have adopted this experimental approach to study the demands of Taekwondo combat (Heller *et al.*, 1998; Matsushigue, Hartmann & Franchini, 2009). This experimental model is associated with a range of difficulties including the constraints of carrying out detailed physiological assessments in this setting and the inability to provide appropriate experimental control of the environment (Drust *et al.*, 2007). A number of alternative experimental approaches may be implemented to circumvent these constraints. Making observations in actual competition using time-motion analysis is a favourable research construct. Time-motion analysis is a non-invasive performance analysis technique that involves the quantification of the mode, frequency and duration of activities performed in competition to determine the energetic requirements of the activity (Hughes & Franks, 2008; Drust, 2010). This information may serve as a valuable ergonomic framework to inform the structure of conditioning sessions for Taekwondo competition and it may permit the development of specific exercise protocols for the purpose of monitoring competitors fitness status (Drust *et al.*, 2007). Regardless of the value of these data, few investigations have examined the activity profiles in Taekwondo competition (Heller *et al.*, 1998; Matsushigue *et al.*, 2009).

An alternative experimental approach favoured by a number of research groups involves the development and use of competition simulations (Drust, Reilly & Cable, 2000; Nicholas, Nuttall & Williams, 2000; Roberts, Stokes, Weston & Trewartha, 2010). These simulations attempt to recreate the activity pattern performed in actual competition while providing greater control of key experimental variables (Drust *et al.*, 2007). This experimental paradigm may permit more detailed examination of the physiological responses to Taekwondo-specific intermittent activity and it may provide a controlled model to facilitate the study of interventions (Drust *et al.*, 2000; Roberts *et al.*, 2010). There have been no attempts to devise an exercise protocol that simulates the activity profile of championship Taekwondo combat.

AIMS AND OBJECTIVES

The aim of the present investigation was to evaluate the physiological demands of competitive Taekwondo. Determination of the physiological demands of this combat sport will be achieved through the fulfilment of several objectives. The objectives of the research were to:

1) Determine the physiological responses to Taekwondo competition and training
2) Examine the activity profiles in Taekwondo competition
3) Devise a simulation of Taekwondo competition
4) Implement the Taekwondo simulation(s) to provide a more detailed examination of the physiological demands of Taekwondo competition.

CHAPTER 2

REVIEW OF LITERATURE

2.1 OVERVIEW

The aim of this section is to provide a comprehensive appraisal of the physiological demands of Taekwondo. The research approaches available to study the physiological demands of sports such as Taekwondo include behavioural observations during competition, physiological evaluations in actual and simulated competition, and the assessment of competitors physical capabilities (Bangsbo, 1994; Drust *et al.*, 2007). An understanding of the physiological demands of training is also required to inform the structure of conditioning sessions for competition (Reilly, 2005). The review, therefore, highlights the characteristics of Taekwondo competition and training, provides a systematic and critical appraisal of the published research in these areas, and offers guidance for future investigations. As few data are available on the physiological demands of Taekwondo competition and training, the review also considers evidence from other combat sports, which contain analogous training and competition structures. It is hoped that this additional information will serve to support the understanding of the physiological demands in areas that Taekwondo-specific research is severely deficient.

2.2 PHYSIOLOGICAL DEMANDS OF TAEKWONDO COMPETITION

2.2.1 Characteristics of Competition

During the formation of ‘World Taekwondo Federation’ in 1973, the first major official international Taekwondo competition the ‘1st Mens World Taekwondo Championships’ was staged (Kim, Chung & Lee, 1999). Since its inception, numerous national, regional and international events have regularly featured within the official WTF competitive programme. In recent years, Taekwondo has been formally recognised as an Olympic sport by the Olympic Movement (Olympic-Movement, 2010). Taekwondo initially featured as an Olympic demonstration sport in 1988 in Seoul, Korea, and remained a demonstration sport in 1992 in Barcelona, Spain. The combat element of Taekwondo was recognised as an official Olympic sport in 1994 and since this date it has regularly featured in the Olympic Games programme. Taekwondo was confirmed as official combat sport for the 2012 Olympic Games, London, United Kingdom and the 2016 Olympic Games, Rio De Janeiro, Brazil (Olympic-Movement, 2010). Since receiving Olympic recognition, the characteristics and structure of Taekwondo competition has transformed and currently varies between different organising bodies and competition levels. The characteristics of competition will be presented according to the WTF’s rules and regulations in this thesis (WTF, 2010). The WTF is responsible for implementing the rules and regulations in Olympic Taekwondo competition.

The combat element of Taekwondo practiced under the administration of the WTF comprises weight-restricted full-contact combat between two opponents. Senior national, regional and international level combats are contested across eight individual weight divisions (Table 2.2.1). In the Olympic Games, Taekwondo combats are contested across four separate weight divisions (Table 2.2.2). Male and female weight divisions are independently classified (Table 2.2.1 and Table 2.2.2). Only individuals within specific weight classes are permitted to compete against each other during competition. The full-contact nature of Taekwondo combat necessitates the use of protective equipment in competition. Competitors are required to wear a trunk protector, head protector, groin guard, forearm guards, shin guards, gloves and a mouthpiece while competing. The objective of combat is to overcome an opponent by obtaining either a greater quantity of points for the execution of kicking and punching techniques to permitted scoring areas or by achieving a technical knockout. Points are awarded for techniques that are executed accurately with ‘sufficient force’ to the designated scoring areas. Permitted scoring areas include the mid-section of the trunk covered by the trunk protector and the whole part of the face. Legitimate techniques include fist techniques delivered with the front parts of the forefinger and middle finger, and foot techniques executed with the parts of the foot below the ankle bone. Both fist and foot techniques are

Table 2.2.1: Weight Categories for WTF sanctioned senior level national, regional and international events

Weight Category	Male Division	Female Division
Fin	Not exceeding 54kg	Not exceeding 47kg
Fly	Over 54kg & not exceeding 58kg	Over 47kg & not exceeding 51kg
Bantam	Over 58kg & not exceeding 62kg	Over 51kg & not exceeding 55kg
Feather	Over 62kg & not exceeding 67kg	Over 55kg & not exceeding 59kg
Light	Over 67kg & not exceeding 72kg	Over 59kg & not exceeding 63kg
Welter	Over 72kg & not exceeding 78kg	Over 63kg & not exceeding 67kg
Middle	Over 78kg & not exceeding 84kg	Over 67kg & not exceeding 72kg
Heavy	Over 84kg	Over 72kg

Information adapted from WTF (2010).

Table 2.2.2: Weight categories for the Olympic Games

Male Division	Female Division
Not exceeding 58kg	Not exceeding 49kg
Over 58kg & not exceeding 68kg	Over 49kg & not exceeding 57kg
Over 68kg & not exceeding 80kg	Over 57kg & not exceeding 67kg
Over 80kg	Over 67kg

Information adapted from WTF (2010).

permitted to areas covered by the chest protector, but not to areas of the back that are exposed from the protector. Foot techniques are permitted to the face, but not to the back of the head. Fist techniques are not permitted to the face under any circumstances. One point is awarded for a successful attack on the trunk protector, two points are awarded for a successful attack on the face and an additional point is awarded for a successful execution that results in a knock down and/or referee count. A competitor may be declared victorious by obtaining a technical knockout, by achieving a 'decision of superiority', or if the opponent is disqualified or withdrawn. A decision of superiority is awarded if a competitor obtains a greater number of points than their opponent over the course of the combat, by reaching the upper limit of twelve points or by achieving a seven-point margin against an opponent. During the contest 'prohibited acts' can also influence the score. Performing a 'prohibited act' during combat may result in either a 'warning penalty' (Kyong-go) or a 'point deduction penalty' (Gam-jeom) being enforced. If two warning penalties are incurred during combat a deduction penalty is enforced and one point is deducted from the overall score. Prohibited acts such as holding, pushing, crossing the boundary line and injury fabrication may result in a warning penalty being enforced. Automatic deduction penalties may be enforced for attacking a fallen opponent, intentionally attacking the face with the hand, and throwing opponents to the ground (WTF, 2010).

Taekwondo combats take place on standard regulation mats within a 'contest area' that comprises specific dimensions (Figure 2.2.1). The contest area is identical for all competitors irrespective of their age, gender, experience and weight category. Taekwondo combats generally comprise three rounds of two-minutes with one-minute recovery between each round, but this can vary with approval from the federation. Combats containing three two-minute rounds with thirty seconds recovery between each round may also be implemented with approval from the WTF. This combat format may be enforced during large-scale international tournaments that contain a large number of competitors. In the event of a 'tie score' after the completion of the full three rounds of combat, a 4^{th} round of 'sudden death' is conducted. The sudden death round lasts two-minutes in duration and usually takes place one-minute following the 3^{rd} round. The first competitor to score a point during sudden death, known as a 'golden point', is adjudicated the winner.

Note: All the rules and regulations presented in this chapter were correct and effective during the data collection periods for all of the studies contained within the thesis (WTF, 2010).

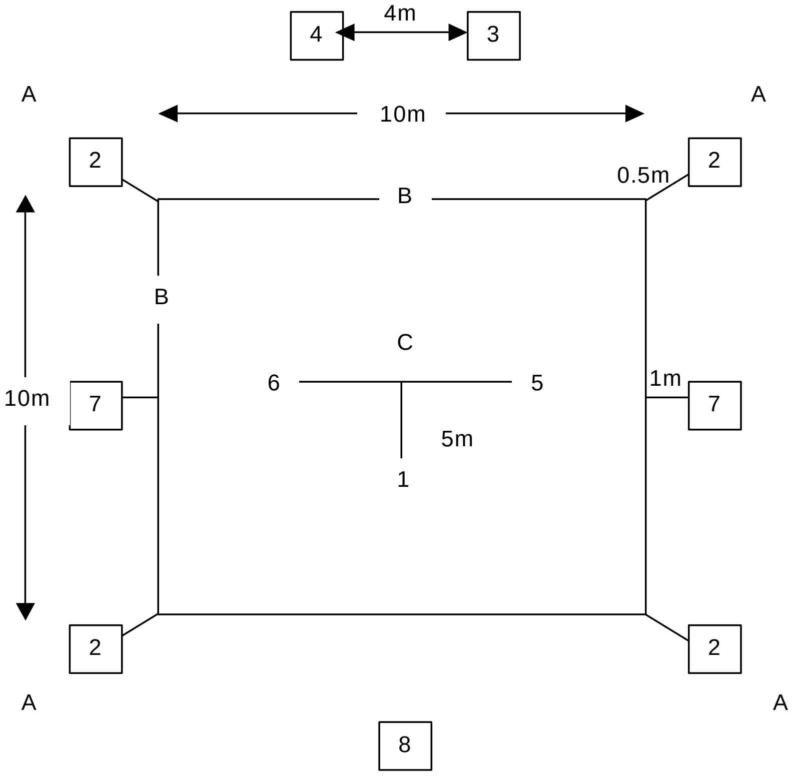


Figure 2.2.1: Taekwondo contest area

A. Field of Taekwondo Play
B. Boundary
C. Contest Area
1. Referees Mark
2. Judges Mark
3. Recorders Mark
4. Doctors Mark
5. Blue Competitors Mark
6. Red Competitors Mark
7. Coaches Mark
8. Camera Position

Adapted from WTF (2010).

2.2.2 Acute Physiological Responses to Combat

2.2.2.1 Heart Rate and Blood Lactate responses

Heart rate and blood lactate measures are routinely collected in a variety of competition settings to quantify the fundamental physiological demands of specific sports (Bangsbo, 1994; Deutsch, Maw, Jenkins & Reaburn, 1998; Heller *et al.*, 1998; Aziz, Tan & Teh, 2002). Heart rate measures are frequently used as an indicator of cardiovascular strain and as a surrogate for oxygen uptake ($\dot{V}O_2$) to estimate the aerobic metabolic requirements of competition settings (Achten & Jeukendrup, 2003). In contrast, blood lactate is commonly used as a marker of anaerobic metabolism, in particular anaerobic glycolysis (Gaitanos, Williams, Boobis & Brooks, 1993; Bangsbo, 1994; Heller *et al.*, 1998). A limited number of investigations have evaluated the HR and blood lactate responses to championship Taekwondo competition (Tables 2.2.3 & 2.2.4). Heller et al. (1998) examined the HR and blood lactate responses to performing Taekwondo combats in a national level championship event. The combats performed in this event were structured according to International Taekwondo Federation (ITF) regulations, which comprised two rounds of two-minutes with one-minute recovery between each round. The activity pattern of combat induced maximal cardiovascular responses (185 beats.min^{-1}; ≈ 100% HRmax) and high post combat blood lactate concentrations (11.4 mmol.l^{-1}) (Heller *et al.*, 1998). These cardiovascular demands compare favourably with less distinguished forms of Taekwondo combat governed by the Songham Taekwondo Federation (STF), but the lactate responses were somewhat higher (Matsushigue *et al.*, 2009). In the STF national level championship event, competitors performed poomse and weapons stages followed by a single two-minute round of Taekwondo combat. The mean HR and blood lactate responses measured on completion of these combats were 183 beats.min^{-1} and 7.5 mmol.l^{-1} respectively (Matsushigue *et al.*, 2009). These findings represent the only attempts to examine the physiological responses in actual championship Taekwondo events. The limited available data collectively suggest that championship Taekwondo combats induce high demands upon both aerobic and anaerobic metabolism.

While these data provide important insights into the energetic requirements of the combat activity, they represent the demands of ITF and STF national level championship events (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). The physiological responses to WTF international level championship combats have never been investigated. The physical capabilities of Taekwondo competitors' vary between levels of experience and competitive success (Toskovic *et al.*, 2004; Markovic *et al.*, 2005). Competition level and training status influence the activity levels in numerous competitive environments (Krustrup, Mohr, Ellingsgaard & Bangsbo, 2005; Sirotic, Coutts, Knowles &

Catterick, 2009; Weston, Castagna, Helsen & Impellizzeri, 2009; Brewer, Dawson, Heasman, Stewart & Cormack, 2010). This would suggest that the available data on the physiological demands of Taekwondo may not be generalisable to other populations of competitors. The discordant regulations and combat formats implemented in these studies raise further concerns surrounding the generalisability of these data to WTF combats. The physiological responses to Taekwondo and Karate combats, for instance, appear to be modulated by both the number of rounds that are performed and the round duration (Heller *et al.*, 1998; Iide *et al.*, 2008; Matsushigue *et al.*, 2009) (Tables 2.2.3 & 2.2.4). It is clear that further research into the physiological demands of WTF international level championship Taekwondo competition is necessary to inform the structure of conditioning sessions for this specific population of competitors.

The available data on the physiological responses to simulated Taekwondo combat, structured according to the WTF regulations, could provide important insights into the demands of actual WTF combat. To this end, a number of investigators have examined the HR and blood lactate responses to performing simulated Taekwondo combat and inferences have then been drawn to the relative physiological loading that is imposed in WTF championship events (Bouhlel *et al.*, 2006; Butios & Tasika, 2007). Bouhlel et al. (2006) evaluated the HR and blood lactate responses of eight male Tunisian national team competitors during a simulated Taekwondo competition event. The simulated event took place in a typical practice setting and the combats comprised three rounds of three-minutes with a one-minute rest interval separating each round. These simulated combats were structured according to the WTF regulations that were effective at the time of the study. The activity pattern of these combat simulations evoked near-maximal cardiovascular responses (99% HRmax) and high post combat blood lactate concentrations (10.2 $mmol.l^{-1}$) (Bouhlel *et al.*, 2006). These findings compare favourably with the physiological responses reported in national level ITF Taekwondo competition (Heller *et al.*, 1998). In contrast, however, a recent investigation into the physiological demands of simulated Taekwondo competition, using an identical WTF combat format, reported markedly lower HR (86% HRmax) and post combat blood lactate profiles (3.4 $mmol.l^{-1}$) (Butios & Tasika, 2007) (Tables 2.2.3 & 2.2.4).

The precise factors that mediate the physiological incongruity between these simulated Taekwondo combat settings are difficult to quantify. This may be a function of a combination of factors such as variation in the competitors' fitness status between the investigations, disparity in the activity levels performed in the combats and/or dissonant stress hormonal responses to these combat settings (Pierce, Kupprat & Harry, 1976; Hoch, Werle & Welder, 1988; Baron *et al.*, 1992; Ferrauti, Neumann, Weber & Keul, 2001; Haneishi *et al.*, 2007). The fidelity of these simulations as analogues of the demands of championship combat may be ultimately dependent upon whether the activity patterns and physiological responses are similar between these settings (Drust *et al.*, 2007). As there have been no attempts to examine these parameters in WTF championship events, the data obtained from these simulations appear to confound, rather than assist, our understanding of the demands of WTF Combat. This reaffirms the need to examine the activity profiles and physiological responses in actual WTF championship events.

There is an emerging body of research evidence to suggest that the physiological demands in a number of combat sports contests may be modulated by the round of combat. A number of these investigations demonstrate a propensity for increased HR and blood lactate responses across the rounds of combat (Tables 2.2.3 & 2.2.4). This trend is apparent in simulated Taekwondo combats, simulated amateur Boxing combats and championship Pencak Silat combats (Ghosh, Goswami & Ahuja, 1995; Aziz *et al.*, 2002; Bouhlel *et al.*, 2006; Butios & Tasika, 2007). Interestingly, however, a significant rise in blood lactate has not been consistently observed across the rounds of simulated Taekwondo combat (Bouhlel *et al.*, 2006) (Table 2.2.4). The data obtained from these simulated Taekwondo combats may, therefore, perplex our understanding of the lactate responses across the rounds of championship Taekwondo combat. Few investigators have made efforts to collect HR and blood lactate measures across the entire three rounds of combat during an actual championship event (Tables 2.2.3 & 2.2.4). Aziz et al. (2002) remain one of the few research groups to successfully achieve this during an actual Pencak Silat championship event. The championship Pencak Silat combats in this study demonstrated a proclivity for increased HR and blood lactate concentrations as the rounds progressed (Aziz *et al.*, 2002). While there is a trend for increased physiological strain across the rounds in a number of combat sports, the majority of these data have not been subjected to formal inferential statistical scrutiny. The only study to apply inferential statistical procedures to examine the physiological responses across the rounds of combat was performed on amateur boxers during a simulated event (Ghosh *et al.*, 1995). Ghosh et al. (1995) identified that 48 to 57 kg boxers exhibited significantly higher mean HR responses in round 3 than in both rounds 1 and 2. Significantly higher blood lactate concentrations were also measured in rounds 2 and 3 than in round 1 in this boxing weight division. These data collectively provide circuitous evidence to suggest that the physiological demands of Taekwondo may be modulated by the round of combat. Further research is necessary to elucidate the physiological responses across the rounds of WTF championship Taekwondo combats. This may provide further insights into the metabolic adjustments that occur during these specific matches.

Table 2.2.3: Mean ± SD heart rate responses to various combat sport competitions and simulated competitions

Reference	**Discipline**		**Mean Heart Rate Beats.min^{-1} (% HRmax)**				**Gender / Experience**	**Number of Subjects**
			Round 1	**Round 2**	**Round 3**	**Mean**		
Heller et al. (1998)	Taekwondo[2]		184 ± 6 (101%)	186 ± 7 (102%)	-	185 ± 7 (102%)	M/E	11
Bouhlel et al. (2006) [s]	Taekwondo[3]		-	-	-	197 ± 2 (99%)[#]	M/E	8
Butios & Tasika (2007) [s]	Taekwondo[3##]		153	160	162	158 (86%)	M/E	24
Matsushigue et al. (2009)	Taekwondo[2]		-	-	-	183 ± 9 (NR)[#]	M/E	14
Aziz et al. (2002)	Pencak Silat[2]		174 ± 10 (89%)	186 ± 7 (95%)	190 ± 8 (97%)	183 ± 8 (93%)	M/E	13
Imamura (1996)	Karate[2]		-	-	-	192 ± 9 (97%)	M/E	6
Imamura (1999) [s]	Karate[3]		-	-	-	157 ± 21 (79%)	M/E	7
Iide (2008) [s]	Karate[2]		-	-	-	160 ± 13 (85%)	M/E	13
	Karate[3]		-	-	-	170 ± 9 (93%)[^]	M/E	13
Ghosh et al. (1995) [s]	Boxing[3]	48-57 kg	175 ± 7 (88%)	179 ± 6 (90%)	186 ± 5 (94%)*	180 ± 6 (91%)	M/A	7
		60-67 kg	172 ± 6 (88%)	176 ± 7 (90%)	183 ± 5 (93%)	177 ± 6 (90%)	M/A	10
		70-90 kg	172 ± 5 (88%)	180 ± 5 (92%)	179 ± 4 (91%)	177 ± 5 (90%)	M/A	9

M = Male, E = Elite, A = Amateur. [S] Data collected during simulated competition. [#] Data represents the mean of 8 competitors at the end of the competition. [2] two minute rounds; [3] three minute rounds. Inferential statistics were only conducted between rounds in the study by Ghosh et al. (1995). * Denotes significantly different from rounds 1 and 2 $P < 0.05$. ^ Denotes significantly different than 2 minute rounds. [##] Mean data calculated from all conditions in the study; NR = not reported.

Table 2.2.4: Mean ± SD blood lactate responses to various combat sport competitions and simulated competitions

Reference	Discipline		Blood Lactate (mmol.l^{-1})					Gender / Experience	No. Subjects
			Pre-bout	**Round 1**	**Round 2**	**Round 3**	**Mean**		
Heller et al. (1998)	Taekwondo[2]		-	-	11.4 ± 3.2[T]	-	11.4 ± 3.2[T]	M/E	11
Bouhlel et al. (2006) [s]	Taekwondo[3]		1.6 ± 0.2	~5[#]	~7[#]	10.2 ± 1.2[N]	-	M/E	8
Buitos & Tasika (2007) [s]	Taekwondo[3##]		1.2	2.6	2.8	3.4[I]	2.9	M/E	24
Matsushigue et al. (2009)	Taekwondo[2]		3.1 ± 2.7	7.5 ± 3.8	-	-	7.5 ± 3.8[N]	M/E	14
Aziz et al (2002)	Pencak Silat[2]		1.9 ± 0.5	9.7 ± 2.3	12.8 ± 3.5	13.1 ± 4.0	12.5 ± 0.4	M/E	13
Serrano et al. (2002)	Judo[5]		-	-	-	-	10.4 ± 0.6[N]	M	13
Degoutte et al. (2003)	Judo[5]		1.2 ± 0.1	-	-	-	12.3 ± 1.8[T]	M	16
Iide et al. (2008) [s]	Karate[2]		1.4 ± 0.3	-	-	-	3.4 ± 1.0[I]	M/E	13
Ghosh et al. (1995) [s]	Boxing[3]	48-57 kg	2.2 ± 0.4	7.2 ± 0.5	9.3 ± 1.7*	9.1 ± 1.1*	8.6 ± 1.5	M/A	7
		60-67 kg	2.2 ± 0.4	7.1 ± 1.3	7.9 ± 1.6	8.6 ± 1.8[N]	7.8 ± 1.6	M/A	10
		70-90 kg	2.9 ± 1.0	8.0 ± 2.4	8.6 ± 1.7	8.6 ± 2.5[N]	8.4 ± 2.1	M/A	9

M = Male, E = Elite, A = Amateur; [S] Data represents simulated rather than actual competition. * Denotes significantly different from round 1. $P < 0.05$. [#] Data is estimated from illustration, descriptive values not presented. Time of post lactate sample: [N] not reported; [I] immediately post; [T] three minutes post. [##] Mean data calculated from all conditions in the study. [2] two minute rounds; [3] three minute rounds; [5] maximum of five minute round.

2.2.2.2 Oxygen Uptake Responses

Heart rate measures are frequently used as a non-invasive surrogate for $\dot{V}O_2$ to estimate the aerobic metabolic requirements of a number of exercise settings (Achten & Jeukendrup, 2003). Continuous HR measures are also used as a reliable and valid index of exercise intensity across a range of intermittent and combat sport exercise settings (Bangsbo, 1994; Heller *et al.*, 1998; Bot & Hollander, 2000; Aziz *et al.*, 2002). It is clear, however, that collecting $\dot{V}O_2$ measures in an actual Taekwondo championship event would be ecologically favourable to quantify the aerobic metabolic requirements of this combat sport. Since $\dot{V}O_2$ measurement techniques contravene the rules and regulations of championship events, it is not surprising that there have been no attempts to examine the $\dot{V}O_2$ responses in this setting. The full-contact nature of Taekwondo techniques (e.g. attacks to the face) is also incongruous with $\dot{V}O_2$ measurement procedures in most combat settings. As such, continuous HR measures continue to be the most practical method of estimating the aerobic demands of championship Taekwondo combats.

In an attempt to circumvent the constraints associated with collecting data in actual competition, a limited number of research groups have made efforts to collect $\dot{V}O_2$ measures in combat simulations that incorporate technical restrictions (e.g. simulated combats that preclude attacks to the face) (Imamura *et al.*, 1999; Iide *et al.*, 2008). Inferences have then been drawn to the relative loading that is imposed in championship combat. This experimental framework has been implicated to study the aerobic demands of Karate combat (Imamura *et al.*, 1999; Iide *et al.*, 2008). Imamura et al. (1999) identified that Karate sparring, comprising three rounds of three-minutes with one-minute rest between each round, elicited $\dot{V}O_2$ into 32% of competitors' maximum oxygen uptake ($\dot{V}O_{2max}$). Iide et al. (2008) examined the $\dot{V}O_2$ responses to Karate sparring structured across both two- and three-minute rounds. The two- and three-minute rounds of Karate combat induced $\dot{V}O_2$ into 42 and 48% of competitors $\dot{V}O_{2max}$ respectively (Iide *et al.*, 2008). These data infer that Karate combats elicit moderate demands on aerobic metabolism (ACSM, 1998). Given the similarities in the basic combat configuration between Karate and Taekwondo, these data could offer some insight into the $\dot{V}O_2$ responses that may be anticipated in Taekwondo combat. It is pertinent to note, however, that the fidelity of the data obtained from these simulation models as analogues of the demands of championship combats may be dependent upon whether the activity profiles and physiological responses (e.g. HR and lactate) are similar in both combat settings (Drust *et al.*, 2007). These Karate simulations, for instance, have evoked substantially lower HR responses than actual championship Karate combats (Imamura *et al.*, 1996). It is clear that further research into the $\dot{V}O_2$ responses to simulated Taekwondo combat is warranted to elucidate the aerobic metabolic requirements of the combat activity. Such investigations may necessitate suitable validity checks to ensure that the activity profiles and physiological responses (e.g. HR and lactate) are similar in both combat settings.

2.2.4 Rating of Perceived Exertion Responses

Perceived exertion can be defined as the act of detecting and interpreting sensations that occur from the body during physical exercise (Noble & Robertson, 1996). This subjective measure of exertion is obtained from specific stimuli. Perceived exertion is governed by a number of physiological and psychological mediators (Noble & Robertson, 1996; Chen, Fan & Moe, 2002). The physiological responses to an acute exercise bout mediate the intensity of the perceptual signals of exertion by acting individually or collectively to alter tension (Noble & Robertson, 1996). Alterations in peripheral and respiratory muscle tension are monitored via the neurophysiological pathway and transmit exertion signals from the motor to the sensory cortex. The neurophysiological signal is consciously interpreted by the sensory cortex as 'effort sense' (Noble & Robertson, 1996). This sensory continuum includes a feedback loop where perceptual information is linked with physiological and neurological events to determine the strength of the exertion responses under various performance conditions (Noble & Robertson, 1996; Chen *et al.*, 2002). The physiological mediators of effort sense may include a number of respiratory-metabolic, peripheral, and non-specific factors (Noble & Robertson, 1996; Chen *et al.*, 2002). The respiratory-metabolic mediators of effort sense include ventilatory drive, $\dot{V}O_2$ consumption, carbon dioxide (CO_2) excretion, HR and blood pressure. The physiological processes that are thought to mediate the intensity of peripheral exertion responses include metabolic acidosis (pH and lactic acid), muscle fibre contractile properties, muscle blood flow and blood-borne energy substrates. Non-specific mediators of effort sense include hormonal regulation (e.g. catecholamines), temperature regulation and exercise induced pain (Noble & Robertson, 1996).

Although there is some debate surrounding the importance of specific mediators in determining perceived exertion (Chen *et al.*, 2002), it is clear that these subjective measures may be used in juxtaposition to physiological parameters to prescribe and monitor the intensity of exercise (ACSM, 1998). Scientists have developed a range of instruments (scales) to monitor the exertional responses during exercise. The most widely used instrument to measure perceived exertion is Borg's rating of perceived exertion (RPE) scale. While variations of this scale exist, the review will focus upon Borg's 6-20 point scale (Borg, 1998). This scale is frequently used in conjunction with physiological indices to prescribe and monitor exercise intensity in a variety of settings (ACSM, 1998). This scale has proven reliability across a range of sports and it has been validated against the specific physiological mediators under investigation in the current thesis (Robertson *et al.*, 1992; Borg, 1998; Chen *et al.*, 2002). Rating of perceived exertion is also sensitive to adjustments in the physical workload and physiological responses (e.g. HR and blood lactate) in both competition (Perez-Landaluce, Rodriguez-Alonso, Fernandez-Garcia, Bustillo-Fernandez & Terrados, 1998; Mendez-Villanueva, Fernandez-Fernandez, Bishop, Fernandez-Garcia & Terrados, 2007; Sinclair, Kerr, Spinks & Leicht, 2009) and training settings (Perez-Landaluce *et al.*, 1998; Impellizzeri, Rampinini, Coutts, Sassi & Marcora, 2004; Little & Williams, 2007).

Regardless of the value of RPE in both practice and research settings, the RPE responses to Taekwondo competition have never been examined. The RPE responses to other combat sports competitions, that exhibit analogous combat formats and physiological responses, could offer some insight into the RPE responses that may be expected in Taekwondo competition. A limited number of studies have examined the RPE responses to Karate and Mixed Martial Arts championship tournaments (Imamura *et al.*, 1996; Amtmann, Amtmann & Spath, 2008). Championship Karate combats, comprising three rounds of two-minutes with one-minute recovery between each round, elicited HR into 97% of competitors' HRmax. The mean RPE during these combats was 19 units, corresponding to 'extremely hard' perceptions of effort (Imamura *et al.*, 1996). Championship Mixed Martial Arts combats, comprising two rounds of four-minutes with one-minute recovery between the rounds, elicited a mean post combat blood lactate concentration of 15.5 $mmol.l^{-1}$. The mean RPE induced by this physiological strain was 17 units, corresponding to 'very hard' perceptions of effort (Amtmann *et al.*, 2008). These data suggest a close association between the physiological load and effort sense in these combat settings. Rating of perceived exertion may, therefore, serve as valuable non-invasive tool to monitor the relative intensity of each combat during a championship event. It remains unclear whether the close association between physiological load and RPE in these combat sports translate to Taekwondo competition. As such, future research should attempt to establish the efficacy of RPE as an indirect method of quantifying the physiological load in championship Taekwondo combats.

2.2.5 Time-motion Analysis

Performing simple visual observations during competition can provide useful information pertaining to the technical, tactical and activity profile of specific sports. Observers are, however, generally left with a recollection of specific situations and information that is limited by subjective interpretation (Bangsbo, 1994). As a consequence, large quantities of valuable information may be overlooked using such simplified observational approaches. To overcome these issues scientists have devised a range of performance analysis techniques that involve the objective and systematic recording of the activities performed in competition (Hughes & Franks, 2004; Hughes & Franks, 2008). Time-motion analysis is a non-invasive performance analysis technique that may provide broader insights into the technical, tactical and physiological demands of Taekwondo combat (Hughes & Franks, 2008; Drust, 2010). This experimental paradigm may be used to quantify the mode, frequency and duration of discrete activities performed in Taekwondo competition, and thereby help to identify differences in these activity levels as a function of various factors. These data may provide an ergonomic framework to inform the structure of conditioning sessions for Taekwondo competition (Hughes & Franks, 2008) and the design of specific exercise protocols for the purpose of monitoring competitors' fitness status (Drust *et al.*, 2007). It may also enable a close examination of the factors related to Taekwondo performance to be determined.

A limited number of investigations have examined the activity profiles of Taekwondo combat with the intent of quantifying its energetic demands (Heller *et al.*, 1998; Matsushigue *et al.*, 2009), and technical and tactical performances (Kazemi, Waalen, Morgan & White, 2006; Kazemi, Casella & Perri, 2009). This approach has been implicated more frequently for determining the incidence of injuries in combat (Koh & Watkinson, 2002; Roh & Watkinson, 2002; Koh, Watkinson & Yoon, 2004; Beis, Pieter & Abatzides, 2007). Studies examining the activity profile of Taekwondo combat, with the intention of elucidating the energetic demands of the sport, are restricted to relatively simplistic evaluations of national level combat. Heller et al. (1998) were the first research group to perform time-motion analysis on eleven male Czech national team Taekwondo competitors during an ITF national level event. The ITF combats were contested across two two-minute rounds with a one-minute rest interval separating the rounds. The findings of this preliminary investigation identified that 18% of the total combat time comprised contact fighting activity, 54% involved non-contact fighting activity and 28% accounted for stoppages enforced by the referee. These activity phases were also set against a time-base to provide an indication of the fighting:non-fighting activity ratios. During the ITF combats, 3-5 s maximal fighting efforts were interspersed with low intensity non-fighting activity periods at ratios ranging between 1:3 and 1:4 (Heller *et al.*, 1998). Time-motion analysis has also been implemented to study the activity profile of STF national level Taekwondo combat (Matsushigue *et al.*, 2009). The STF combats were structured across a single round lasting two minutes in duration. The mean fighting:non-fighting ratio performed during the STF combats was 1:6 (Matsushigue *et al.*, 2009), which is considerably higher than the fighting:non-fighting ratios performed in ITF combat (Heller *et al.*, 1998). The disparity in the fighting:non-fighting ratios between these investigations may be a function of differences in the combat styles, competition levels and/or the classification systems used to determine the activity profiles. As these data were collected from combats organised under different governing bodies (that implement discordant regulations and combat formats), it may limit their generalisability to WTF competition. As such, a comprehensive appraisal of the activity profiles in WTF Taekwondo combat would seem necessary.

There is an emerging body of research evidence to suggest that the activity profile in Taekwondo combat may be modulated by a multitude of factors. A recent investigation into the technical and tactical performances in Olympic Taekwondo combat, for instance, demonstrates that the number of successful scoring techniques performed by male competitors was influenced by the round of combat (Kazemi *et al.*, 2006). The number of successful scoring techniques was significantly higher in round 1 (54%) than in rounds 2 (31%) and 3 (15%) in these Olympic style combats (Kazemi *et al.*, 2006). A comprehensive appraisal of the activity levels performed within each round was not, however, undertaken in this study. As such, it would seem useful to determine whether specific changes in the activity occur across the rounds of WTF combat.

Studies that have examined the activity profile of Taekwondo combat with the intent of quantifying its energetic demands (Matsushigue *et al.*, 2009), and technical and tactical performances (Kazemi *et al.*, 2006) provide compelling evidence to suggest that the activity profile may also be modulated by a competitor’s level of success (e.g. win or lose). In STF national level combats, successful competitors performed significantly fewer fighting techniques (n = 19) than their unsuccessful counterparts (n = 35) (Matsushigue *et al.*, 2009). This phenomenon was attributed to a reduced technical efficacy and a greater accumulation of penalty points in the unsuccessful group of competitors. In WTF Olympic Taekwondo combats, successful male competitors demonstrated a tendency to perform less frequent offensive techniques than their unsuccessful counterparts (54 vs. 63% respectively) (Kazemi *et al.*, 2006). This finding was a direct consequence of the successful competitors performing more frequent defensive techniques (e.g. counter-attacking). While these data provide evidence to suggest that the basic activity profile of Taekwondo combat may be modulated by a competitor’s level of success, this phenomenon has not been explicitly explored in WTF international level combat.

Investigations into the technical and tactical profiles of Olympic Taekwondo combat provide evidence to suggest that the activity profile may also be modulated by a competitor’s weight category. The number of offensive and defensive techniques performed in combat, for instance, varies considerably between the four male Olympic weight divisions (Kazemi *et al.*, 2009). The total number of offensive techniques performed (n) by the 68-80 kg competitors (n = 216) was significantly greater than those performed by the 58-68 kg (n = 189), +80 kg (n = 117) and the -58 kg (n = 104) competitors. A similar trend was evident for the defensive technical performances for these Olympic weight divisions (Kazemi *et al.*, 2009). Investigations into the injury profiles in WTF Taekwondo combat also provide circuitous evidence to suggest that the activity profile may be influenced by a competitor's weight category. Both the incidence of kicking techniques and the number of injuries accruing from such techniques demonstrate substantial variability between the eight standard male WTF weight divisions (Koh, Freitas & Watkinson, 2001; Koh & Watkinson, 2002). No attempts have been made, however, to compare the activity levels of different WTF weight divisions in the context of determining the energetic requirements. This information may permit conditioning sessions to be specialised to the specific activity requirements of different weight divisions.

2.2.5.1 Time-motion Analysis: Methodological Considerations

The characteristics of a time-motion classification system require careful consideration prior to evaluating the activity profile of Taekwondo competition. The amount of detail contained within a classification system may affect both the time required to analyse the data and its usefulness (Drust *et al.*, 2007). The inclusion of a limited number of categories within a classification system may result in insufficient detail for the data to be meaningful. In contrast, a system that contains to many categories may become too complex and almost impossible to interpret (Drust *et al.*, 2007). The development of a time-motion classification system to study the activity profile of Taekwondo combat should, therefore, provide an effective compromise between assessment practicality and sufficient detail to ensure that the data is meaningful. In most cases, the methods that have been used to collect activity profile data in Taekwondo have either not been reported or contain insufficient detail to permit a comprehensive examination of the combat activity (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). As such, future investigations should consider developing a more complete time-motion classification system to study the activity profile of Taekwondo combat.

The efficacy of the data generated from activity profile assessments in Taekwondo may be dependent upon the reliability and objectivity of the time-motion classification system. In this context, 'reliability' refers to the level of agreement between repeated observations (by the same observer) of the same behaviour or measurement (Drust *et al.*, 2007). 'Objectivity' on the other hand, refers the level of agreement between different observers on the same behaviour or measurement (Drust *et al.*, 2007). These concepts are also described as 'within-observer' and ‘between-observer’ error within the literature. The effectiveness of a time-motion classification system in determining differences in the activity levels between categorical variables (e.g. between the rounds of combat, competition levels, weight categories and investigations) may be dependent upon its reliability and objectivity. The available data on the activity profile of Taekwondo combat has been generated without adequate consideration of the reliability and objectivity of the time-motion classification system (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). This issue is important as it dictates the outcomes and conclusions that can be drawn from the results. A reliable and objective time-motion classification system should, therefore, be developed to facilitate the study of the activity profiles in Taekwondo competition in future. The reliability and objectivity of a time-motion classification system should be determined *a priori* to being implemented to study the physical activity requirements of this combat sport.

2.3 PHYSIOLOGICAL DEMANDS OF TAEKWONDO TRAINING

2.3.1 Characteristics of Training

Performance in Taekwondo competition is ultimately determined by a competitors technical, tactical, physiological and psychological/social characteristics (Pieter & Heijmans, 2003). Taekwondo training sessions are, therefore, structured to target these specific performance mediators (Kim *et al.*, 1999; Pieter & Heijmans, 2000). Conventional Taekwondo practices may contain a wide array of activities that share similar characteristics to other combat sports. Activities such as basic techniques, technical combinations, predetermined sequences of movement (forms, poomsae, or kata), breaking techniques, self-defence techniques, combat sparring drills, and free combat sparring are regular constitutes of traditional forms of Taekwondo practice (Kim *et al.*, 1999; Whang, Whang & Saltz, 1999; Hornsey, 2002; ITF, 2006; WTF, 2010). While the composition of these activities within a typical Taekwondo training session may vary between different Taekwondo teams/clubs, organisations, and competitive cycles within a periodised training programme, these fundamental activities are universally practiced in Taekwondo (Kim *et al.*, 1999; Whang *et al.*, 1999; Hornsey, 2002; ITF, 2006; WTF, 2010). These specific Taekwondo activities are often supplemented with generic strength and conditioning practices (Pieter & Heijmans, 2003). The characteristics of these conventional Taekwondo training activities are presented in Table 2.3.1. Many of these Taekwondo training activities are regarded as technical and tactical practices, but they are regularly performed with the intention of eliciting specific structural and functional adaptations (Pieter & Heijmans, 2000; Pieter & Heijmans, 2003). Kicking technical combinations, for example, may be used to develop a competitor’s technical and tactical aptitude, but they are frequently performed to elicit a suitable stimulus for physical conditioning. Since structural and functional adaptations, and physical performances are closely linked to the specific nature of the training stimulus (Campos *et al.*, 2002; Reilly *et al.*, 2009), it would seem necessary to elucidate the physiological responses to performing different Taekwondo training activities. This information may be valuable to inform the structure of conditioning sessions for competition (Reilly, 2005).

Table 2.3.1: Characteristics of conventional Taekwondo training activities

Activity	**Definition**
Basic techniques	The interchangeable practice of single punching, hand striking, kicking, blocking and stepping techniques executed on the coaches' command. Basic techniques are also known as fundamental techniques.
Technical combinations	A variety of basic techniques executed in various combinations. A combination comprises the consecutive execution of two or more basic techniques.
Forms	Predetermined sequences of basic techniques that range in complexity and length. Forms are practiced either completely or they are separated into smaller segments on the coaches command. These techniques are also known as poomsae, patterns and kata.
Breaking techniques	The forceful execution of basic techniques upon structures, commonly wood, with the intent of breaking each structure.
Self-defence techniques	Self-defence techniques include numerous basic and applied techniques such as locks, holds, take downs, elbow strikes and the release from holds. The objective of these practices is to improve self defence actions for non-competition settings.
Step sparring	One-step prearranged attacks with random counter-attacks performed for coach defined periods. Roles are reversed on the coach's command.
Sparring drills	Pre-arranged attacking and counter-attacking kicking drills practiced repeatedly in pairs making contact with body armour for resistance. These are also known as skill drills.

Table 2.3.1: Continued

Activity	Definition
Free sparring	Open combat between two participants in a free-moving situation (non pre-arranged fighting). Free sparring is usually performed for coach defined periods, sometimes in a manner that replicates competition. Free sparring is also known as contact sparring.
Elastics*	Basic techniques including punches and kicks are practiced continuously utilising elastic stretch bands for additional resistance. Elastic stretch bands are attached to appropriate body segments and single basic techniques are executed in a repetitive manner for coach defined periods.
Pad work*	The practice of basic techniques and technical combinations that make contact with pads for additional resistance.

* Activities are modified by the inclusion of additional resistance. These definitions were formulated utilising information from the following references (Park & Seabourne, 1997; Kim *et al.*, 1999; Whang *et al.*, 1999; Pieter & Heijmans, 2000; Hornsey, 2002; ITF, 2006; WTF, 2010)

2.3.2 Acute Physiological Responses to Training

2.3.2.1 Heart Rate and Oxygen Uptake Responses

Few investigators have examined the cardio-respiratory responses to Taekwondo training (Table 2.3.2). Pieter et al. (1990) were the first research group to examine the cardiovascular responses to performing forms and technical combinations using recreational Taekwondo practitioners. The findings of this initial investigation demonstrated that the practice of two different forms, Kich'oil bu (80% HRmax) and T'aeguki jang (80% HRmax), elicited similar cardiovascular intensities (Table 2.3.2). Research into the cardiovascular demands of forms practice in Taekwondo appears to be limited to this single investigation. Similar cardiovascular intensities have been reported with the practice of forms in Kung Fu (76 to 82% HRmax) (Jones & Unnithan, 1998), but a range of responses have been elicited by forms practice in Karate (68 to 102% HRmax) (Table 2.3.2) (Schmidt & Royer, 1973; Shaw & Deutsch, 1982; Zehr & Sale, 1993; Francescato, Talon & di Prampero, 1995; Imamura *et al.*, 1999; Imamura *et al.*, 2002). The disparity in the cardiovascular responses between these studies may be a function of differences in the complexity of the forms routines, the nature of the muscle actions (Hietanen, 1984), the intensities of practice (Kravitz, Greene, Burkett & Wongsathikun, 2003), the work:rest ratios (Ballor & Volovsek, 1992) and/or the practitioners level of experience (Jones & Unnithan, 1998). Pieter et al. (1990) also examined the HR responses to performing two different Taekwondo technical combinations. The first combination comprised kicking techniques and the second punching and kicking techniques. These kicking (91% HRmax), and kicking and punching technical combinations (91% HRmax) elicited congruent cardiovascular intensities. The data obtained from this fundamental investigation demonstrate that the practice of forms and technical combinations mediate diverse cardiovascular responses (Pieter, Taaffe & Heijmans, 1990). The practice of technical combinations would presumably incite more pronounced cardio-respiratory adaptations than forms practice (Helgerud *et al.*, 2007).

The cardiovascular intensities elicited by the practice of technical combinations in this fundamental investigation compare favourably with the practice intensities of basic techniques and technical combinations in a simulated 'Dynamic Taekwondo' training session (Toskovic, Blessing & Williford, 2002). Toskovic et al. (2002) examined the cardio-respiratory responses to performing a simulated twenty-minute 'Dynamic Taekwondo' session using both experienced and novice Taekwondo practitioners. The combined practice of basic techniques and technical combinations during this session elicited mean HR responses into 90 and 92% of HRmax in the experienced and novice male practitioners respectively. The corresponding $\dot{V}O_2$ responses for both groups of practitioners in this study was 72% of $\dot{V}O_{2max}$ (Toskovic *et al.*, 2002). These data collectively suggest that the practice of technical combinations elicit 'hard' to 'very hard' cardio-respiratory exercise intensities (ACSM, 1990, 1998).

Bouhel et al. (2006) examined the cardiovascular responses to performing repeated Taekwondo front kicks (basic techniques) in a continuous manner across three separate exercise durations. The maximum HR values recorded while performing continuous kicking techniques for durations of 10, 60 and 180 s were 91, 92 and 100% of HRmax respectively (Note: This investigation reported the maximum HR achieved during these practices as opposed to the mean HR). These data suggest that the HR responses to performing basic techniques are sensitive to adjustments in the practice duration (Bouhlel *et al.*, 2006). The maximum HR responses to the practice of basic techniques in this study are similar to the mean HR responses elicited by the practice of basic techniques and technical combinations in previous investigations (Pieter *et al.*, 1990; Toskovic *et al.*, 2002). The cardiovascular intensities elicited by these training techniques compare favourably with those measured in national level Taekwondo competition (Heller *et al.*, 1998; Matsushigue *et al.*, 2009).

This would suggest that a number of these technical practices may be suitable for developing and maintaining cardiovascular fitness for competition.

While the available data provide valuable insights the cardio-respiratory requirements of specific Taekwondo training activities, it may be criticised on the grounds of 'ecological validity'. For the purpose of this thesis the term 'ecological validity' refers specifically to the interaction of the Taekwondo athletes with their natural training environment and practices. These investigations have examined training simulations in laboratory environments, utilising inexperienced participants, and unrealistic work to rest ratios, number of actions, durations and intensities of practice (Pieter *et al.*, 1990; Toskovic *et al.*, 2002; Bouhlel *et al.*, 2006). Pieter et al. (1990), for instance, examined the HR responses to performing Taekwondo forms and technical combinations using recreational practitioners that were enrolled in an intermediate class. Rather than employing typical training durations and work to rest ratios, a ratio of 1:2 was selected on the premise that it represented the minimum work interval that was necessary to elicit cardiovascular adaptations (Pieter *et al.*, 1990). These investigators also highlighted that the number forms performed in their study and in previous investigations was not representative of usual practice. Toskovic et al. (2002), on the other hand, examined the HR and $\dot{V}O_2$ responses to performing a simulated twenty-minute 'Dynamic Taekwondo' training session. Dynamic Taekwondo actions are performed in a more persistent and dynamic manner than traditional and competitive forms of Taekwondo practice (Toskovic *et al.*, 2002). The HR responses to performing continuous front kicks for varying durations has also been examined (Bouhlel *et al.*, 2006). Practicing Taekwondo activities in this format is, however, incongruous with the intermittent character of usual Taekwondo training.

The low ecological validity demonstrated by these training settings may have important implications for the usefulness of the data. Indeed, the physiological responses to training in a number of combat sports are responsive to adjustments in the intensity (speed of execution), duration and work to rest intervals (Table 2.3.2). Zehr and Sale (1993), for instance, studied the physiological responses to performing the same Karate kata at different speeds and for different durations. The 'FAST' kata required the practitioners to perform the kata at competitive pace ($\approx$ 60 s in duration), a structure that typifies both training and competition settings. Whereas the 'PACE' kata required the practitioners to perform the kata twice as fast ($\approx$ 30 s in duration). While the difference in the HR responses to performing these katas was not statistically significant (FAST: 93% HRmax vs. PACE: 101% HRmax), the $\dot{V}O_2$ response to performing the PACE kata was significantly greater than in the FAST kata (94 vs. 73% of peak maximum oxygen uptake [VO_{2peak}] respectively).

Table 2.3.2: Heart rate and oxygen uptake responses to combat sport training activities (Data are mean ± SD unless stated otherwise)

Reference	Discipline	Training Activities	HR (beats.min^{-1})	%HRmax	$\dot{V}O_2$ (ml.kg^{-1}min^{-1})	% $\dot{V}O_{2max}$	Sex / Experience	Number of Subjects
Toskovic et al. (2002)	Taekwondo	Simulated Dynamic	182 ± 8	92 ± 3*a*	39.0 ± 2.5^	72 ± 6*a*	M/N	7
		Taekwondo Session	170 ± 15	90 ± 6*a*	42.0 ± 5.6^	72 ± 7*a*	M/E	7
		(Basics and Technique	173 ± 12	90 ± 6*a*	30.8 ± 4.3	69 ± 10*a*	F/N	7
		Combinations)	168 ± 10	88 ± 5*a*	33.9 ± 2.6	68 ± 8*a*	F/E	7
Pieter et al. (1990)	Taekwondo	Technical Combination I	183 ± NA*	91 ± NA*b**	NA	NA	M/R	8
		Technical Combination II	181 ± NA*	91 ± NA*b**				
		Forms (Kich'oil bu)	160 ± NA	80 ± NA*b*				
		Forms (T'aeguki jang)	159 ± NA	80 ± NA*b*				
				Data are Maximum HR				
Bouhel (2006)	Taekwondo	Continuous kicks (10s)	NA	91 ± NA*e*	NA	NA	M/E	8
		Continuous kicks (60s)		92 ± NA*e*				
		Continuous kicks (180s)		100 ± NA*e*				
Imamura et al. (2002)	Karate	Basic techniques (stationary)	103 ± 11	53 ± 5	*9.7 ± 0.6*	23 ± 2	F/E	6
		Basic techniques (stances)	144 ± 14	75 ± 7	*20.6 ± 2.1*	49 ± 5		
		Sparring (without opponent)	143 ± 14	74 ± 7	*17 ± 1.6*	41 ± 5		
		Sparring (with opponent)	137 ± 9	71 ± 6	*14.6 ± 1*	35 ± 2		
		Kata (forms)	135 ± 10	70 ± 5	*14.9 ± 0.7*	35 ± 2		

Table 2.3.2: Continued

Reference	Discipline	Training Activities	HR (beats.min^{-1})	%HR max	$\dot{V}O_2$ (ml.kg^{-1}min^{-1})	% $\dot{V}O_{2max}$	Sex / Experience	Number of Subjects
Imamura et al. (1999)	Karate	Basic techniques (stationary)	114 ± 21	58 ± 11	*17.0 ± 4.1*	29 ± 7	M/E	7
		Basic techniques (various stances)	151 ± 19	76 ± 9	*31.3 ± 5.5*	54 ± 9		
		Sparring (without opponent)	157 ± 21	79 ± 12	*31.7 ± 4.2*	55 ± 8		
		Sparring (with opponent)	152 ± 17	77 ± 9	*32.1 ± 5.9*	55 ± 9		
		Kata (forms)	149 ± 16	75 ± 9	*25.6 ± 3.0*	44 ± 4		
Imamura et al. (1997)	Karate	1000 Continuous Punches	103 ± 15	53 ± 9*a*			M/E	6
			116 ± 18	58 ± 8*a*	NA	NA	M/N	8
		1000 Continuous Kicks	127 ± 12[#]	66 ± 8*a*[#]			M/E	6
			137 ± 14[#]	70 ± 7*a*[#]			M/N	8
Francescato et al. (1995)	Karate	Forms (Pinan ni dan Kata)						
		10 seconds (s)	134 ± 22	*68 ± 11b*	14.4 ± 4.2	*39 ± 11c*	M	8
		20 s	142 ± 33	*72 ± 17b*	14.9 ± 5.4	*41 ± 17c*		8
		30 s	151 ± 27	*77 ± 14b*	20.1 ± 3.3	*55 ± 9c*		8
		40 s	163 ± 12	*83 ± 6b*	25.5 ± 4.0	*69 ± 11c*		8
		60 s	160 ± 7	*82 ± 4b*	27.1 ± 4.8	*74 ± 13c*		4
		80 s	166 ± 12	*85 ± 6b*	27.5 ± 4.6	*75 ± 13c*		4

Table 2.3.2: Continued

Reference	**Discipline**	**Training Activities**	**HR (beats.min^{-1})**	**%HR max**	$\dot{V}O_2$ **(ml.kg^{-1}min^{-1})**	**%** $\dot{V}O_{2max}$	**Sex / Experience**	**Number of Subjects**
Zehr and Sale (1993)	Karate	Forms (Seisan Kata)				%VO2 Peak		
		PACE = Competition style	158 ± 14	93 ± 6*c*	33.3 ± 2.6	73 ± 3*c*	M/E	4
				94 ± 8d		*84 ± 7d*		
		FAST = Twice as fast as	172 ± 10	101 ± 3*c*	43.6 ± 5.7	94 ± 2*c*□	M/E	4
		PACE		*102 ± 6d*		*110 ± 14d*□		
Shaw and Deutsch (1982)	Karate	Forms (Hein Shodan Kata) x15	Data are Mean ± SE					
		30s Continuous	168 ± 4	*86 ± 2a*	31.1 ± 1.5	55 ± 2*a*		
		45s Continuous	148 ± 5	*76 ± 2a*	25.6 ± 1.5	45 ± 2*a*	MF/N	10
		Mean of both Continuous	158 ± 3△	*81 ± 2a*	28.4 ± 1.1△	50 ± 2*a*△		
		30s Intermittent (1min rest)	140 ± 4	*72 ± 2a*	20.4 ± 0.9	36 ± 1*a*		
		45s Intermittent (1min rest)	138 ± 4	*71 ± 2a*	17.3 ± 0.9	31 ± 1*a*		
		Mean of both Intermittent	139 ± 3	*71 ± 1a*	18.8 ± 0.7	34 ± 1*a*		
		Mean of both 30s	154 ± 3▲	*79 ± 2a*	25.7 ± 1.1▲	46 ± 2*a*▲		
		Mean of both 45s	143 ± 3	*73 ± 2a*	21.5 ± 1.0	38 ± 2*a*		
Schmidt and Royer (1973)	Karate	Forms (15 different katas)	Data are Maximum HR					
		Average of all 15 Kata data are reported	145 ± NA	*74 ± NAb*	NA	NA	M/E	1

Table 2.3.2 Continued

Reference	Discipline	Training Activities	HR (beats.min^{-1})	%HR max	$\dot{V}O_2$ (ml.kg^{-1}min^{-1})	% $\dot{V}O_{2max}$	Sex / Experience	Number of Subjects
Jones and	Kung Fu	Forms (Chat Seng)		76 ± 4*c*		72 ± 5*c*	M/E	9
Unnithan (1998)				82 ± 4*c*$^{>}$		82 ± 6*c*$^{>}$	M/N	9
		Continuous Single Punches		64 ± 4*c*		38 ± 2*c*	M/E	
		(30 s intervals)	NA	82 ± 4*c*	NA	41 ± 3*c*	M/N	
				66 ± 4*d*		46 ± 5*d*	M/E	
				85 ± 5*d*$^{>}$		55 ± 7*d*$^{>}$	M/N	
		Continuous Single Kicks		75 ± 4*c*		64 ± 3*c*^{I}	M/E	
		(30 s intervals)		82 ± 3*c*$^{>}$		54 ± 4*c*^{I}	M/N	
Heller (2000)	Multi-	Nunchaku Exercise						
	Discipline	20 s	130 ± 16	69 ± NA*c*	23.5 ± NA	43 ± NA*c*	M/E	9
		60 s (1min)	137 ± 16^{+}	72 ± NA*c*	26.0 ± NA	49 ± NA*c*		
		300 s (5min)	144 ± 14^{+}◓	76 ± NA*c*	29.9 ±NA^{+}◓	56 ± NA*c*		

M = Male, F = Female, E = Experienced, N = Novice, R = Recreational, HR = Heart Rate, %HRmax = Percentage of Heart Rate Maximum. NA = Data Not Published. Values presented in *italics* have been calculated from available data.

a = Maximum values measured utilising treadmill test
b = Maximum values predicted utilising equation (220-age)
c = Maximum values measured utilising leg cycle ergometer test
d = Maximum values measured utilising arm cycle ergometer test
e = Maximum values measured during competition

* = Combinations Significantly Higher HR than Forms ($P < 0.05$)
□ = Significantly different than pace kata ($P < 0.05$)
\# = Kicks Significantly Higher HR than Punches ($P < 0.05$)
$^{>}$ = Novice Significantly Higher HR/VO2 than Experienced ($P < 0.05$)
^ = Males significantly greater VO2 than females ($P < 0.05$)
^{I} = Interaction effect ($P < 0.05$)
△ = Mean continuous format significantly different from mean intermittent format ($P < 0.05$)
▲ = Mean 30s format significantly different from mean 45s format ($P < 0.05$)
$^{+}$ = Significantly different from 20s exercise trial ($P < 0.05$)
◓ = Significantly different from 1 minute exercise trial ($P < 0.05$)

Further evidence of the responsiveness of the physiological responses to changes in the duration and format of training is abundant within the combat sports literature (Table 2.3.2). Shaw and Deutsch (1982), for instance, investigated the physiological responses to performing Karate kata for different durations, and in both continuous and intermittent formats (Table 2.3.2). In this investigation, Karate kata was practiced continuously and intermittently for 30 and 45 s. When the continuous and intermittent exercise modes were examined as a collective group the mean HR for the 30 s practice (154 beats.min^{-1}) was significantly higher than the 45 s practice (143 beats.min^{-1}). This study also identified significantly higher HR responses when the kata was performed in a continuous (158 beats.min^{-1}) as opposed to an intermittent format (139 beats.min^{-1}). This response was evident irrespective of the practice duration. A similar trend was also apparent for the $\dot{V}O_2$ responses in this investigation (Table 2.3.2). Heller et al. (2000) investigated the HR and $\dot{V}O_2$ responses to performing nunchaku exercise for durations of 20, 60 and 300 s using mixed martial arts practitioners. The mean HR for the 300 s nunchaku practice (144 beats.min^{-1}) was significantly higher than in both the 60 s (137 beats.min^{-1}) and 20 s (130 beats.min^{-1}) practice durations. A similar trend was also evident for the $\dot{V}O_2$ responses in this investigation (Table 2.3.2).

These data collectively provide compelling evidence to suggest that the intensity, duration and work to rest intervals modulate the physiological responses to combat sport practices. The available Taekwondo training data may, therefore, provide a disingenuous representation of the physiological responses to performing traditional and competitive forms of training in an ecologically valid setting. It is clear that further research into the physiological demands of ecologically valid Taekwondo training practices is warranted. To conform to the requirements ecological validity, future investigations should incorporate field assessments, and utilise realistic work to rest ratios, number of actions, intensities and durations of practice. The structure and proportion of activities within typical training environments should also be taken into consideration.

2.3.2.2 Blood Lactate Responses

To date, only one investigation has examined the blood lactate responses to Taekwondo training. Bouhel et al. (2006) examined the blood lactate responses to performing continuous front kicks for varying durations. Performing continuous kicking techniques for exercise durations of 10, 60 and 180 s evoked mean post-exercise blood lactate concentrations of ≈ 1, 10 and 9 mmol.l^{-1} respectively (Bouhlel *et al.*, 2006) (these data were estimated from the figures in the research paper because the descriptive statistics were not presented). These data clearly demonstrate that the blood lactate responses to performing continuous front kicks are modulated by the practice duration. The mean blood lactate concentration elicited by the 10 s Taekwondo kicking practice in this study is similar to the low range of lactate concentrations measured in various karate practices (1.2 to 3.0 $mmol.l^{-1}$) (Imamura *et al.*, 1997; Imamura *et al.*, 1999; Imamura *et al.*, 2002). Whereas, the mean blood lactate concentrations elicited by the 60 and 180 s Taekwondo kicking practices compare more favourably to the lactate concentrations measured in mixed martial arts practices (16.5 $mmol.l^{-1}$) (Amtmann *et al.*, 2008). The blood lactate concentrations elicited by the 60 and 180 s Taekwondo kicking practices are also similar to those measured in national level Taekwondo competition (Heller *et al.*, 1998). This would suggest that these technical practices may be suitable to prepare competitors' for the anaerobic metabolic requirements of Taekwondo competition. The execution of continuous front kicks for long durations is, however, incongruous with the intermittent character of conventional training and competition settings (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). No attempts have been made to examine the blood lactate responses to performing conventional Taekwondo activities in an ecologically valid setting.

Collecting blood samples in actual training settings would be ecologically favourable to determine the lactate responses to performing specific Taekwondo activities. There are, however, a number of constraints that may limit the effectiveness of this strategy. Collecting blood samples from large volumes of practitioners during the simultaneous practice of activities may be restricted by the availability of equipment and the number of sufficiently trained personnel. In this environment, blood lactate may reflect, but underestimate, the lactate production in the minutes prior to sampling (Bangsbo, 1994). Peak blood lactate concentrations also occur at different time intervals after exercise (Hirvonen, Rehunen, Rusko & Harkonen, 1987). As such, blood samples may need to be collected and processed at similar times for each practitioner. This approach may also necessitate repeated blood sampling after each specific activity during the session and may require sampling to be undertaken across a number of different sessions. Researchers may need to consider these issues in the design of future investigations into the physiological demands of training.

2.3.3 Rating of Perceived Exertion Responses

Subjective measures of exertion are commonly used in concert to physiological indices to prescribe and monitor the intensity of training (ACSM, 1998; Little & Williams, 2007). Borg's 6-20 RPE scale is one of the most widely used instruments in this process (Chen *et al.*, 2002). This scale is sensitive to adjustments in both the physical workload and physiological responses (e.g. HR and blood lactate) in a number of training settings (Perez-Landaluce *et al.*, 1998; Impellizzeri *et al.*, 2004; Little & Williams, 2007). In training settings that appreciably activate both aerobic and anaerobic metabolism, the combined use of RPE and physiological measures may be more effective in regulating the intensity of exercise than the use of physiological indices alone (Little & Williams, 2007). Before subjective measures can be effectively used to prescribe and monitor the intensity of training, the RPE scale should be validated across a wide range of sport-specific activities and physiological loads (Little & Williams, 2007). The successful validation of RPE across a range of Taekwondo activities, and physiological loads may provide coaches and practitioners with a less invasive and/or more efficient means of regulating the intensity of training.

To date, only one study has examined the RPE responses to Taekwondo training. Toskovic et al. (2002) evaluated the RPE responses to performing twenty-minutes of 'dynamic Taekwondo' training. In this investigation RPE was recorded alongside measures of HR and $\dot{V}O_2$ using Borg's 6-20 scale (Borg, 1998). The dynamic Taekwondo training session elicited mean HR and $\dot{V}O_2$ responses into 90 and 72% of practitioners HRmax and $\dot{V}O_{2max}$, respectively. The mean RPE evoked by this physiological strain was 13 units, corresponding to 'somewhat hard' perceptions of effort. Unfortunately, however, these data represent the RPE responses to performing twenty-minutes of dynamic Taekwondo activity. These data may not be generalisable to conventional forms of intermittent Taekwondo training (Table 2.3.2). A further point of contention is that the data represent the RPE responses of the entire session as opposed to providing detailed information about the discrete activities performed within the session (Toskovic *et al.*, 2002). As such, the available data provide no information concerning validity of RPE as a marker of exercise intensity across a wide range Taekwondo activities and physiological loads. It is clear that further research into the RPE responses to Taekwondo training is warranted.

2.4 PHYSICAL CAPABILITIES OF TAEKWONDO ATHLETES

2.4.1 Applications of Physical Capacity Testing

Physical performance tests provide useful information concerning the physical capabilities of athletes and they assist in the monitoring of fitness status. In an applied practice setting, physical performance tests are valuable to identify strengths and weaknesses in an individual's physical attributes, to monitor fitness status over time and to verify the effectiveness of specific training interventions (Svensson & Drust, 2005). In a research context, the information collected from physical performance testing may be used to indirectly quantify the physiological demands of specific sports (Bangsbo, 1994; Drust *et al.*, 2007). This concept is based on the assumption that elite athletes have adapted to the regular physiological requirements of competition (Bangsbo, 1994). The information obtained from physical capacity testing may be used to identify physical attributes that are favourable for competitive success and it may serve as a useful indicator of the minimum fitness standards required to compete at specific levels of competition (Heller *et al.*, 1998; Markovic *et al.*, 2005; Franchini, Nunes, Moraes & Del Vecchio, 2007). This experimental approach may also be used to detect differences in competitors physical attributes as a function of various factors such as competition levels, positional roles, genders and weight categories (Callister *et al.*, 1991; Bangsbo, 1994; Yoon, 2002; Toskovic *et al.*, 2004; Khanna & Manna, 2006). Inferences are then drawn to the relative physiological loading that is imposed by these specific competition factors. As such, the available data on the physical capabilities of Taekwondo competitors should be considered in the quantification of the physiological demands of this combat sport. A number of investigations have examined the physical capabilities of Taekwondo athletes (Table 2.4.1) (Pieter, 1991; Thompson & Vinueza, 1991; Heller *et al.*, 1998; Toskovic *et al.*, 2004; Markovic *et al.*, 2005; Bouhlel *et al.*, 2006). These studies will be considered in the context of determining the energetic demands of Taekwondo combat.

Table 2.4.1: Taekwondo practitioners' anthropometric and physical characteristics

Fitness Measure	Component of Fitness	Reference and Procedure	Results (mean ± SD, unless stated otherwise)	
			Males	Females
General Characteristics of the Sample	Number of Subjects (Data represent sum)	Bouhlel et al. (2006)	8	-
		Butios and Tasika (2007)	24	-
		Markovic et al. (2005)	-	6^{S}
			-	7^{LS}
		Toskovic et al. (2004)	$7^{E\ N}$	$7^{E\ N}$
		Heller et al. (1998)	11	12
		Thompson and Vinueza (1991)	14	-
		Pieter (1991)	27	-
	Training Experience (years)	Bouhlel et al. (2006)	7	-
		Markovic et al. (2005)	-	Range: 7-10
		Toskovic et al. (2004)	$11.3^{E\wedge}$	$6.1^{E\wedge}$
			0.2^{N}	0.2^{N}
		Heller et al. (1998)	Range: 4-6	Range: 4-6
		Thompson and Vinueza (1991)	4.1 ± 4.7	-
	Training Frequency (days per week)	Bouhlel et al. (2006)	5	-
		Butios and Tasika (2007)	5	-
		Markovic et al. (2005)	-	5
		Toskovic et al. (2004)	4^{E}	2^{E}
			2^{N}	2^{N}
		Heller et al. (1998)	Range: 3-5	Range: 3-5
		Thompson and Vinueza (1991)	Range: 2-3	-

Table 2.4.1: Continued

Fitness Measure	Component of Fitness	Reference and Procedure	Results (mean ± SD, unless stated otherwise)	
			Males	Females
	Competitive Status	Bouhlel et al. (2006)	Regularly competing for the Tunisian national team	
		Butios and Tasika (2007)	Regularly competing in South Korea	
		Markovic et al. (2005)	Regularly competing for the Croatian national team	
		Toskovic et al. (2004)	Recreational non-competitive	
		Heller et al. (1998)	Regularly competing for the Czech national team	
		Thompson and Vinueza (1991)	National Club level athletes	
		Pieter (1991)	Regularly competing for the USA national team	
Anthropometric Characteristics	Age (years)	Bouhlel et al. (2006)	20 ± 1	-
		Butios and Tasika (2007)	22 ± 1	-
		Markovic et al. (2005)	-	22 ± 4^{S}
			-	21 ± 4^{LS}
		Toskovic et al. (2004)	25 ± 9$^{E\#}$	31 ± 8$^{E\#}$
			21 ± 3^{N}	21 ± 1^{N}
		Heller et al. (1998)	21 ± 2	19 ± 3
		Thompson and Vinueza (1991)	28 ± 4	-
		Pieter (1991)	24 ± 5	26 ± 5

Table 2.4.1: Continued

Fitness Measure	Component of Fitness	Reference and Procedure	Results (mean ± SD, unless stated otherwise)	
			Males	Females
Anthropometric Characteristics	Height (cm)	Bouhlel et al. (2006)	180 ± 4	-
		Butios and Tasika (2007)	180 ± 8	-
		Markovic et al. (2005)	-	171.1 ± 5.4^{S}
			-	165.3 ± 6.6^{LS}
		Toskovic et al. (2004)	173.6 ± 7.7$^{E\#}$	162.7 ± 6.6^{E}
			178.4 ± 7.4$^{N\#}$	163.4 ± 2.7^{N}
		Heller et al. (1998)	179 ± 6	168 ± 5
		Thompson and Vinueza (1991)	173.7 ± 6.4	-
		Pieter (1991)	178.6 ± 8.3	171.5 ± 8.3
	Body fat (%)	Bouhlel et al. (2006): 4 skin fold measures	11.8 ± 3	-
		Markovic et al. (2005): 4 skin fold measures	-	15.3 ± 2.0^{S}
			-	17.6 ± 2.9^{LS}
		Toskovic et al. (2004): 7 skin fold measures	12.7 ± 3.6$^{E\#\wedge}$	16.1 ± 3.8$^{E\wedge}$
			16.0 ± 5.4$^{N\#}$	20.3 ± 3.9^{N}
		Heller et al. (1998): 10 skin fold measures	8.2 ± 3.1	15.4 ± 5.1
		Thompson and Vinueza (1991): Hydrostatic weighing	18.9 ± 5.4	-

Table 2.4.1: Continued

Fitness Measure	Component of Fitness	Reference and Procedure	Results (mean $\pm$ SD, unless stated otherwise)	
			Males	Females
Aerobic Performance	$\dot{V}O_{2max}$ (ml.kg^{-1}.min^{-1})	Bouhlel et al. (2006): Multistage 20 meter shuttle test	56.2 ± 2.6	-
		Butios and Tasika (2007): Multistage 20 meter shuttle test	53.9 ± 4.1	-
		Markovic et al. (2005): Progressive treadmill test	-	49.6 ± 3.3^{S}
			-	47.2 ± 2.1^{LS}
		Toskovic et al. (2004): Progressive treadmill test	$58.9 \pm 8.2^{E\#\wedge}$	$50.5 \pm 6.1^{E\wedge}$
			$54.3 \pm 3.2^{N\#}$	44.7 ± 4.3^{N}
		Heller et al. (1998): Cycle ergometer based test	53.9 ± 4.4	41.6 ± 4.2
		Thompson and Vinueza (1991): Progressive treadmill test	44.0 ± 6.8	-
		Pieter (1991): Not reported	55.8 ± 3.9	47.0 ± 7
	Maximum speed at $\dot{V}O_{2max}$ (Km.h^{-1})	Markovic et al. (2005): Progressive treadmill test	-	$15.8 \pm 0.5^{S*}$
			-	14.9 ± 0.7^{LS}
	Ventilatory Threshold (ml.kg^{-1}.min^{-1})	Markovic et al. (2005): Progressive treadmill test	-	$41.4 \pm 4.1^{S*}$
			-	37.6 ± 2.0^{LS}

Table 2.4.1: Continued

Fitness Measure	Component of Fitness	Reference and Procedure	Results (mean ± SD, unless stated otherwise)	
			Males	Females
Anaerobic Performance	Peak Power ($W.kg^{-1}$)	Bouhlel et al. (2006): 7 s force velocity test with breaking forces of 2.5% of body mass, which increased to 5% then 1% thereafter until exhaustion	12.1 ± 1.7	-
		Heller et al. (1998): 30 s Wingate with loads of 6 $w.kg^{-1}$ and 5 $w.kg^{-1}$ for males and females respectively	14.7 ± 1.3	10.1 ± 1.2
		Pieter (1991): 30 s Wingate (loads not reported)	11.8 ± 2.0	10.2 ± 2.5
	Mean Power ($W.kg^{-1}$)	Heller et al. (1998): 30 s Wingate with loads of 6 $w.kg^{-1}$ and 5 $w.kg^{-1}$ for males and females respectively	5.7 ± 0.4	4.0 ± 0.4
		Pieter (1991): 30 s Wingate (loads not reported)	9.2 ± 1.2	7.9 ± 1.2
	Fatigue Index (%)	Heller et al. (1998): 30 s Wingate with loads of 6 $w.kg^{-1}$ and 5 $w.kg^{-1}$ for males and females respectively	42.2 ± 7.3	37.8 ± 6.6
		Pieter (1991): 30 s Wingate (loads not reported)	37.9 ± 14.8	37.7 ± 13.6

Table 2.4.1: Continued

Fitness Measure	Component of Fitness	Reference and Procedure		Results (mean ± SD, unless stated otherwise)	
				Males	**Females**
Strength (Units provided with the values)	Explosive Strength (power)	Heller et al. (1998):	Counter Movement Jump (Kistler force platform)	45.4 ± 4.5 cm	29.8 ± 4 cm
		Markovic et al. (2005):	Squat Jump (Electronic Jump Mat)	-	29.8 ± 2.9 cm^{S}
					27.7 ± 2.4 cm^{LS}
			Counter Movement Jump (Electronic Jump Mat)		32.8 ± 3.9 cm^{S}*
				-	28.7 ± 1.9 cm^{LS}
			Counter Movement Jump with arm swing (Electronic Jump Mat)		36.4 ± 3.5 cm^{S}*
				-	33.2 ± 2.3 cm^{LS}
			Repetitive Jumps (RJ5) (Electronic Jump Mat)	-	31.7 ± 1.9 cm^{S}
				-	29.1 ± 3.5 cm^{LS}
			15 second jumps (Electronic Jump Mat)	-	27.0 ± 2.6 W.kg^{-1S} *
				-	22.1 ± 2.1 W.kg$^{-1\ LS}$
			20m Sprint	-	3.6 ± 0.2 s ^{S}*
				-	3.8 ± 0.1 s ^{LS}
		Toskovic et al. (2004):	Vertical jump with arm reach (Electronic Jump Mat)	51.5 ± 8.6 $^{E\#\wedge}$	31.3 ± 3.1 cm ^{E}
				43.7 ± 5.0 $^{N\#}$	32.1 ± 3.4 cm ^{N}

Table 2.4.1: Continued

Fitness Measure	Component of Fitness	Reference and Procedure	Results (mean $\pm$ SD, unless stated otherwise)	
			Males	**Females**
Strength	Maximum Strength	Markovic et al. (2005): Bench Press 1RM (free weights)	-	55.7 $\pm$ 11.6 kg ^{S}
(Units provided			-	0.9 $\pm$ 0.1 kg.bw ^{S}
with values)			-	48.5 $\pm$ 8.2 kg ^{LS}
			-	0.8 $\pm$ 0.1 kg.bw ^{LS}
		Markovic et al. (2005): Back Squat 1RM (free weights)	-	89.1 $\pm$ 17.6 kg ^{S}
			-	1.43 $\pm$ 0.2 kg.bw ^{S}
			-	72.1 $\pm$ 15.2 kg ^{LS}
			-	1.2 $\pm$ 0.2 kg.bw ^{LS}
		Toskovic et al. (2004): Bench Press 1RM (machine based)	84.3 $\pm$ 23.9 kg $^{E\#}$	37.1 $\pm$ 13.3 kg ^{E}
			1.23 $\pm$ 0.3 kg.bw $^{E\#}$	0.62 $\pm$ 0.1 kg.bw ^{E}
			86.1 $\pm$ 26.8 kg $^{N\#}$	36.1 $\pm$ 7.9 kg ^{N}
			1.06 $\pm$ 0.3 kg.bw $^{N\#}$	0.57 $\pm$ 0.1 kg.bw ^{N}
		Toskovic et al. (2004): Leg Press 1RM (machine based)	217.1 $\pm$ 42.3 kg $^{E\#}$	151.4 $\pm$ 30.2 kg ^{E}
			3.2 $\pm$ 0.6 kg.bw $^{E\#}$	2.6 $\pm$ 0.5 kg.bw ^{E}
			196.4 $\pm$ 33.0 kg $^{N\#}$	147.9 $\pm$ 25.0 kg ^{N}
			2.4 $\pm$ 0.6 kg.bw $^{N\#}$	2.3 $\pm$ 0.4 kg.bw ^{N}

Notes: S = Successful at major competitions; *LS* = Less successful a major competitions; *E* = Experienced Taekwondo practitioners; *N* = Novice Taekwondo practitioners.

* Denotes successful competitors are significantly different than less successful competitors ($P < 0.05$). $^{\#}$ Denotes male group significantly different than female group ($P < 0.05$), $^{\wedge}$ Denotes experienced practitioner group is significantly different than novice practitioner group ($P < 0.05$).

2.4.2 Anthropometric Characteristics

The mean age of Taekwondo practitioners' reported in the literature ranges between 20-27 years and 19-31 years for males and females respectively (Table 2.4.1). The limited available data in this area suggest that age is not an key mediator of competitive success amid elite competitors (Markovic *et al.*, 2005). The mean age of elite Taekwondo competitors in the literature does, however, seem to be confined within relatively narrow limits. Male and female competitors, for instance, tend to compete at the highest level of competition between the age of 20-24 years and 19-22 years respectively (Table 2.4.1). The upper age range reported for males (25-28 years) and females (31 years) in the literature represent those individuals that partake in Taekwondo training for recreational purposes (Table 2.4.1). The factors that govern this trend remain elusive. This may be a function of a number of factors such as age related declines in physiological function (Rittweger, di Prampero, Maffulli & Narici, 2009), the perception that injury risk is inflated with age (Pieter, 2005), and/or external factors including restricted funding opportunities, the desire to establish a family and the need to pursue a career outside of the realm of Taekwondo. It is also possible that the highly demanding nature of Taekwondo competition (Heller *et al.*, 1998) and training (Pieter *et al.*, 1990; Bouhlel *et al.*, 2006) is more suited to this population.

The average height of male and female Taekwondo practitioners reported in the literature ranges between 174-180 cm and 163-172 cm respectively (Table 2.4.1). A number of investigators postulate that longer lower extremities may be advantageous in combat sports where leg techniques constitute the predominant means of attack (Markovic *et al.*, 2005; Kazemi *et al.*, 2006). While several studies demonstrate that successful Taekwondo competitors were on average taller than their less successful counterparts, these data did not reach statistical significance (Markovic *et al.*, 2005; Kazemi *et al.*, 2006). It appears then, that the technical and tactical advantages associated with the stature of an individual do not manifest performance changes that influence the match outcome. Although stature does not appear to influence success in this combat sport, it may play a pivotal role in determining a competitor's fighting weight division. In support of this presumption, a strong correlation between stature and weight division has been established in a number of weight-regulated combat sports (Callister *et al.*, 1991; Franchini, Del Vecchio, Matsushigue & Artioli, 2011).

The body fat percentages of male and female Taekwondo practitioners' reported in the literature range between 8.2-18.9% and 15.3-20.3% respectively (Table 2.4.1). The lower range of body fat values exhibited by male Taekwondo exponents in comparison to females is consistent with the normative data reported across a range of sports (Hoffman, 2006). Elite male Taekwondo competitors (8.2-11.8%) demonstrate a propensity for lower body fat than their non-competitive counterparts (12.7-18.9%) (Table 2.4.1). The body fat percentages of these elite male Taekwondo competitors' compare favourably with male competitors' involved in a number of weight-regulated combat sports such as Karate (10.7-12.6%), Pencak Silat (11.3%), Kick Boxing (8.1%), Judo (8.3 to 11.2%) and Boxing (12.2 to 16.4%) (Callister *et al.*, 1991; Imamura, Yamakoshi, Uchida, Nishimura & Nakazawa, 1998; Aziz *et al.*, 2002; Guidetti, Musulin & Baldari, 2002; Khanna & Manna, 2006; Franchini *et al.*, 2007). The variation in body composition between the competitive and non-competitive male Taekwondo practitioners in the literature may be a function of a number of factors including differences in the practitioners training volumes (Table 2.4.1), nutritional practices and the requirements to 'make the weight' for competition (Fleming & Costarelli, 2007; Tsai, Ko, Chang, Chou & Fang, 2010; Tsai, Chou, Chang & Fang, 2011).

2.4.3 Aerobic Performance Abilities

A number of investigators have examined the aerobic capabilities of recreational and competitive Taekwondo practitioners by estimating and measuring $\dot{V}O_{2max}$ (Table 2.4.1). The range of $\dot{V}O_{2max}$ values reported for male and female Taekwondo competitors that were actively competing in championship events were 44-56 ml.kg^{-1}min^{-1} and 42-50 ml.kg^{-1}min^{-1}, respectively (Table 2.4.1). The range of $\dot{V}O_{2max}$ values reported for the male Taekwondo competitors' in the literature compare favourably with the aerobic capabilities of male competitors in Karate (51-58 ml.kg^{-1}min^{-1}) and Pencak Silat (52 ml.kg^{-1}min^{-1}), but Judo (48-63 ml.kg^{-1}min^{-1}), Amateur Boxing (62-64 ml.kg^{-1}min^{-1}), Kickboxing (63 ml.kg^{-1}min^{-1}) and Wrestling exponents (48-63 ml.kg^{-1}min^{-1}) demonstrate markedly higher aerobic capacity ranges (Zabukovec & Tiidus, 1995; Imamura *et al.*, 1998; Aziz *et al.*, 2002; Yoon, 2002; Khanna & Manna, 2006; Smith, 2006; Iide *et al.*, 2008). The range of $\dot{V}O_{2max}$ values demonstrated by the male Taekwondo competitors' in the literature are also markedly lower than those exhibited by a number of other athletic populations (Bangsbo, 1994; Faria, Parker & Faria, 2005; Midgley, McNaughton & Wilkinson, 2006; Winter, Jones, Davison, Bromley & Mercer, 2007).

If inferences are drawn from the available Taekwondo $\dot{V}O_{2max}$ data to the relative physiological loading imposed in actual combat (Bangsbo, 1994), it would suggest that Taekwondo competition elicits low to moderate demands on aerobic metabolism. As such, high levels of cardio-respiratory fitness may not be an essential requirement for performance in this combat sport. In support of this notion, no significant differences in $\dot{V}O_{2max}$ have been identified between successful and less successful female Taekwondo competitors (Markovic *et al.*, 2005). Interestingly, however, successful female competitors demonstrate significantly higher ventilatory thresholds than their less successful counterparts (Table 2.4.1). The practical significance of this finding in relation to Taekwondo performance is unknown. While the $\dot{V}O_{2max}$ values of competitive Taekwondo competitors may provide circuitous evidence to suggest that Taekwondo competition imposes relatively low to moderate demands on aerobic metabolism, this contrasts the HR responses measured in championship competition (e.g. ≈ 100% HRmax) (Heller *et al.*, 1998). This notion is also incongruous with the typical structure of Taekwondo competition, which may require competitors' to compete in up to 5 combats within a single day. As aerobic metabolism fuels the recovery processes between high-intensity exercise bouts (Borsheim & Bahr, 2003), a reasonable level of cardio-respiratory fitness would seem necessary for this population of competitors. The available data on the $\dot{V}O_{2max}$ of Taekwondo competitors appear to confound, rather than assist, our understanding of the aerobic metabolic requirements of combat.

2.4.4 Anaerobic Performance Abilities

Several studies have examined the anaerobic performance abilities of both recreational and competitive Taekwondo practitioners (Table 2.4.1). A number of investigators have studied the 'anaerobic capacities' of national and international level Taekwondo competitors using the established 30 s Wingate protocol (Inbar, Bar-Or & Skinner, 1996). The range of peak power values generated by national and international level Taekwondo competitors using this protocol were 12.1-14.7 $W.kg^{-1}$ and 10.1-10.2 $W.kg^{-1}$ for males and females respectively (Pieter, 1991; Heller *et al.*, 1998; Bouhlel *et al.*, 2006). The peak power values generated by the male Taekwondo competitors in these investigations compare favourably with the peak power values produced by male Pencak Silat exponents (12.8 $W.kg^{-1}$), Judo competitors (13.7 $W.kg^{-1}$) and Wrestlers (11.2 $W.kg^{-1}$), but considerably higher values have been elicited by Kickboxers (18.8 $W.kg^{-1}$) (Little, 1991; Zabukovec & Tiidus, 1995; Aziz *et al.*, 2002; Yoon, 2002). The range of peak power values produced by these different combat sport competitors are similar to those generated by competitors involved in other explosive/power based events (Faria, Parker & Faria, 2005; Winter *et al.*, 2007). They are also ranked amid the highest percentile norms for physically active males aged between 18 and 28 years (Maud & Foster, 2006). These data suggest that the ability to generate high peak power may be an important requirement for Taekwondo competition.

The mean power values generated by national and international level Taekwondo competitors using the 30 s Wingate protocol range between 5.7-9.2 $W.kg^{-1}$ and 4.0-7.9 $W.kg^{-1}$ for males and females respectively (Pieter, 1991; Heller *et al.*, 1998). The mean power values situated towards the higher end of the male data range are similar to those generated by male competitors in Pencak Silat (9.3 $W.kg^{-1}$), Judo (10.6 $W.kg^{-1}$) and Kickboxing (10.5 $W.kg^{-1}$) (Little, 1991; Zabukovec & Tiidus, 1995; Aziz *et al.*, 2002). Whereas the mean power values situated towards the lower end of the male data range compare more favourably to the values produced by Wrestling exponents (6.7 $W.kg^{-1}$) (Yoon, 2002). While there are some methodological differences between the 30 s Wingate protocols used to assess both peak and mean power output in the literature (Table 2.4.1), the available data suggest that a high anaerobic capacity may be an important requirement for Taekwondo competition. If these data are extrapolated to the relative physiological loading that is imposed in competition (Bangsbo, 1994), it would suggest that Taekwondo combats elicit high demands upon anaerobic metabolism. This presumption may be supported by the high blood lactate concentrations measured in Taekwondo competition (e.g. 11.4 $mmol.l^{-1}$) (Heller *et al.*, 1998).

The available data on the strength and power profiles of Taekwondo competitors support the notion that Taekwondo competition places high demands upon anaerobic metabolism (Table 2.4.1). The mean height recorded for the counter movement jump (CMJ), for instance, ranges between 45-52 cm and 30-33 cm for male and female Taekwondo competitors, respectively (Table 2.4.1). The CMJ performances for the male Taekwondo competitors in these investigations concur with those performed by male Judo competitors, Pencak Silat exponents and elite competitors involved in a range of other explosive/power based events (Aziz *et al.*, 2002; Winter *et al.*, 2007). The high CMJ performances exhibited by these Taekwondo competitors represent the high explosive properties of the lower limbs in this population of athletes (Table 2.4.1). As few data are available on the explosive power profiles of male Taekwondo competitors, it is important to consider evidence from female Taekwondo competitors. The available data demonstrate that successful female Taekwondo competitors exhibit superior explosive lower limb performances than their less successful counterparts (Table 2.4.1) (Markovic *et al.*, 2005). This is evidenced by the successful competitors higher CMJ, 15 s jump power and 20 m sprint performances (Table 2.4.1). This suggests that high explosive properties of the lower limbs may be a prerequisite for competition success in Taekwondo.

An appraisal of Taekwondo competitors' maximum strength profiles is a little more challenging due to the limited available literature in this area and the lack of standardisation of the strength assessment techniques between the investigations (Table 2.4.1). Despite this, Taekwondo competitors mean 1RM bench press performances are generally ranked within the 80^{th} (males) and 100^{th} (females) percentile of the normative values for the general athletic population aged between 20 to 29 years (Hoffman, 2006). Taekwondo competitors mean 1RM leg press performances are ranked well above the 100^{th} (males and females) percentile of the normative values for the general athletic population (Hoffman, 2006). Successful and less successful Taekwondo competitors seem to exhibit comparable maximum strength performances (Table 2.4.1). As such, these data suggest that both upper and lower body musculature is important for Taekwondo competition, yet these attributes may not be crucial determinants of competition success.

In summary, national and international level Taekwondo competitors' demonstrate high anaerobic performance abilities with less exceptional aerobic performance abilities (Table 2.4.1). These data may provide an indirect insight into the physiological demands of Taekwondo competition. This concept is based on the assumption that elite competitors have adapted to the regular physiological requirements of competition (Bangsbo, 1994). This rationale is somewhat simplistic though, as performance on such tests may reflect the demands of current training practices (Toskovic *et al.*, 2004; Mohr *et al.*, 2007), and the influence of individuals genetic endowment (Lippi *et al.*, 2009) and health status as opposed to the adaptation to the regular physiological stress of competition. Indeed, this rationale does not correspond with the irregular competition schedule in modern-day Taekwondo. As such, these approaches may not accurately represent the demands of this combat sport. Direct evaluations of the acute physiological responses to simulated and championship competition may, therefore, offer a more effective method of quantifying the physiological demands of this combat sport.

2.5 COMPETITION SIMULATIONS

2.5.1 Theoretical rationale for the implementation of competition simulations

Collecting physiological measures in an actual championship event would be ecologically favourable to advance knowledge of the acute physiological demands of Taekwondo combat (Hoch *et al.*, 1988; Chiodo *et al.*, 2009). A number of constraints have been identified by adopting this experimental approach (Drust *et al.*, 2007). Firstly, the methods that can be used to determine the physiological responses during competition are restricted by both the event regulations and the competitors' desire to engage in invasive procedures. The latter issue is particularly prevalent when the match outcome has significant implications for the athlete. Secondly, competition settings are not associated with the same degree of experimental control that is provided in the laboratory. As such, variation in the competitors' performances between matches may preclude the study of interventions in actual competition.

In an attempt to circumvent these constraints, a number of research groups have devised simulations of competition for a range of sports (Drust *et al.*, 2000; Nicholas *et al.*, 2000; Kraemer *et al.*, 2001; Davey, Thorpe & Willams, 2003; Thatcher & Batterham, 2004; Greig, McNaughton & Lovell, 2006; Kingsley, James, Kilduff, Dietzig & Dietzig, 2006; Drust *et al.*, 2007; Hayes, van

Paridon, French, Thomas & Gordon, 2009; Roberts *et al.*, 2010). Two main experimental models have been favoured in this endeavour. The first simulation model favoured by a number of combat sport researchers involves formulating a full-contact version of combat against an opponent in a practice or laboratory setting. In this environment, combats are usually contested according to the regulations of the sports governing body. It is widely accepted that this setting is not subjected to the same degree of experimental control that is provided by other simulation models. This simulation framework does have the added benefit of including all of the activities that are performed in actual competition (e.g. feints, blocks and the impacts received from an opponent) and it has the potential to incite significant emotional strain in individuals (Hoch *et al.*, 1988). This simulation model has been implicated to study the physiological demands of combat in Taekwondo (Bouhlel *et al.*, 2006), Wrestling (Kraemer *et al.*, 2001), Boxing (Ghosh *et al.*, 1995; Khanna & Manna, 2006; Smith, 2006), Karate (Imamura *et al.*, 1999; Iide *et al.*, 2008), Judo (Franchini, de Moraes Bertuzzi, Takito & Kiss, 2009) and Fencing (Hoch *et al.*, 1988). This experimental framework has also been used to examine the influence of specific interventions on the physiological responses in combat (Kraemer *et al.*, 2001; Franchini *et al.*, 2009). As such, this simulation model seems to be appropriate to circumvent some of the constraints associated with collecting physiological measures in actual competition. This model may be particularly suited to experimental designs that intend to examine the physiological demands of the combat activity and do not necessitate meticulous control of the environment.

The second simulation model favoured by researchers in a range of intermittent sports involves devising an exercise protocol that serves to replicate the activity profile and physiological responses of competition in a controlled setting (Drust *et al.*, 2007). These exercise protocols usually require individuals to execute movements in predetermined sequences, which are governed by specific cues (e.g. visual or audio stimuli). This simulation model has the advantage of providing appropriate control of key experimental variables to permit the study of interventions (Drust *et al.*, 2000; Thompson *et al.*, 2001; Morris, Nevill, Thompson, Collie & Williams, 2003; Roberts *et al.*, 2010). It may also permit more detailed evaluations of the physiological responses to sports-specific intermittent exercise (Drust *et al.*, 2000). There are, however, several inherent limitations associated with this simulation model. The degree of experimental control required in this simulation framework often precludes the inclusion of some sport specific actions. This requirement may also restrict the number of activity changes that can be performed (Drust *et al.*, 2000). These omissions may lead to reductions in the overall energy requirements in comparison to actual competition. Despite these limitations, the majority of the exercise protocols available in the literature provide reasonable approximations of the activity patterns and the relative physiological loading that is imposed in actual competition. To date, such protocols have been successfully devised for Soccer (Drust *et al.*, 2000; Nicholas *et al.*, 2000; Thatcher & Batterham, 2004; Greig *et* *al.*, 2006), Tennis (Davey *et al.*, 2003), Squash (Kingsley *et al.*, 2006) Golf (Hayes *et al.*, 2009) and more recently Rugby Union (Roberts *et al.*, 2010). The degree of experimental control provided by these protocols has enabled researchers to effectively study the influence of pre-cooling (Drust, Cable & Reilly, 2000), carbohydrate-electrolyte solutions (Morris *et al.*, 2003), caffeine and carbohydrate solutions (Roberts *et al.*, 2010), heat acclimatisation strategies (Sunderland, Morris & Nevill, 2008), muscle fatigue (Rahnama, Reilly, Lees & Graham-Smith, 2003) and injury risk (Greig, 2008) on the physiological and performance responses to sports-specific intermittent exercise. As such, this simulation model seems to be particularly suited to investigations that require high levels of experimental control and that necessitate the use of invasive experimental procedures. Regardless of the value of this experimental approach, there have been no attempts to devise an exercise protocol that serves to replicate the activity profile and physiological responses of Taekwondo competition. Detailed investigations into the activity profiles and physiological responses of Taekwondo competition are, however, required before a Taekwondo simulation can be developed, validated and effectively used to study the demands of combat.

2.5.2 Validity and Reliability Considerations

The effectiveness of competition simulations as analogues of the physiological demands of competition can be assessed by comparing the activity patterns and physiological responses to these settings (Drust *et al.*, 2007). A large proportion of the 'exercise-protocol' based competition simulations in the literature attempt to broadly replicate the activity patterns of competition in that they make efforts to reproduce the locomotion profile (e.g. periods of walking, jogging, crusing, sprinting and standing) (Drust *et al.*, 2000; Nicholas *et al.*, 2000; Thatcher & Batterham, 2004; Greig *et al.*, 2006). A number of these competition simulations have also made efforts to replicate the technical actions of the sport in juxtaposition to the locomotion activity (Davey *et al.*, 2003; Kingsley *et al.*, 2006; Hayes *et al.*, 2009; Roberts *et al.*, 2010). The construct validity of these competition simulations has been determined by comparing the mode, frequency and duration of actions performed in the exercise protocol and competition (Drust *et al.*, 2000; Davey *et al.*, 2003; Greig *et al.*, 2006; Roberts *et al.*, 2010). The work:rest intervals, distance covered and proportion of actions have also been considered by investigators in a number of these validity checks (Kingsley *et al.*, 2006; Hayes *et al.*, 2009; Roberts *et al.*, 2010). The majority of the simulations in the literature also attempt to recreate the relative physiological loading that is imposed in competition. This correspondence has been determined by comparing the physiological (e.g. HR, blood lactate, blood glucose and changes in body mass) and RPE responses to these settings (Drust *et al.*, 2000; Nicholas *et al.*, 2000; Davey *et al.*, 2003; Thatcher & Batterham, 2004; Kingsley *et al.*, 2006; Hayes *et al.*, 2009; Roberts *et al.*, 2010). The vast majority of the competition simulations in the literature seem to provide close approximations of the technical and/or locomotion profiles performed in competition, and they demonstrate analogous physiological responses.

As alluded to earlier, the major criticisms of the available competition simulations include the inability to incorporate the entire range of activities that are typically performed in competition and the failure to replicate the high frequency of activity changes (Drust *et al.*, 2007). Concerns have also been raised about the methods that have been used to validate the physiological load in a number of investigations (Drust *et al.*, 2007). A number of investigations have made attempts to validate the physiological responses to the simulation with those published in the literature (Drust *et al.*, 2000; Nicholas *et al.*, 2000; Davey *et al.*, 2003; Greig *et al.*, 2006; Roberts *et al.*, 2010). This approach is probably a consequence of the difficulties in obtaining suitable physiological measures from participants in both settings. While this is an entirely acceptable means of validating the physiological load, examining the same participants under both simulation and competition conditions may optimise this validity check (Drust *et al.*, 2007). This point in no way undermines the existing validity checks; it is merely a suggestion to optimise this method in instances where the environment permits the implementation of this strategy. It is fully acknowledged that researchers in this setting are required to operate in challenging circumstances and that they are limited by various constraints. This approach to validating the physiological load has been successfully adopted in several recent investigations (Thatcher & Batterham, 2004; Kingsley *et al.*, 2006; Hayes *et al.*, 2009). Researchers may, therefore, be able to alleviate some of the complexities associated with this approach by refining aspects of this simulation model. At present, this simulation model seems to provide an effective compromise between external and internal validity in that it provides a close approximation of the physiological demands of competition while maintaining suitable control of the environment to permit the study of interventions.

Prior to implementing a competition simulation into a repeated-measures research design, it is important to consider the reliability of the physiological and performance responses. Reliability, in this context, may be defined as the consistency of measures of an individual’s performance on a test (Atkinson & Nevill, 1998) or the level of agreement between repeated observations of the same behaviour or phenomenon (Drust *et al.*, 2007). An exercise protocol that demonstrates inadequate reproducibility may not be sensitive enough to detect small meaningful changes in performance and physiological function as a consequence of specific interventions (Currell & Jeukendrup, 2008). Any attempts to develop a competition simulation in Taekwondo should, therefore, subject the physiological and performance responses to formal reliability checks.

Nicholas et al. (2000) determined the reliability of the performance times in the LIST using Bland and Altman’s 95% limits of agreement (LOA). The 95 % LOA for the sprint times during part A and the time to exhaustion during part B were –0.14 to 0.12 s and -3.19 to 2.16 minutes respectively. The reliability of the physiological responses elicited by the LIST were assessed by means of a two-way (treatment x time) repeated measures analysis of variance (ANOVA). No significant differences were identified in any of the physiological parameters between the test and re-test trials. The authors therefore concluded that the LIST protocol was a reliable and valuable measurement tool to study the influence of interventions on the physiological and performance responses to soccer-specific intermittent exercise.

Roberts et al. (2010) determined the reliability of the performance times and physiological responses in the Bath University Rugby Shuttle Test (BURST) using the technical error of measurement (TEM). The TEM values were expressed in both absolute and percentage forms (coefficient of variation [CV]). The average 15m sprint times and rugby-specific test performances obtained from two trials of the BURST returned CV values ranging between 0.9 and 3.9 %. The CV values for RPE, HR, blood glucose, blood lactate and the change in body mass obtained from the two trials were 1.6 %, 2.2 %, 5.0 %, 14.4 % and 12.4 % respectively. The authors deduced that the low CV values for the performance tests demonstrate suitable reliability to allow the detection of relatively small adjustments arising from particular interventions (Roberts *et al.*, 2010). While the physiological responses tended to return larger CV values than the performance measures, they also seem to demonstrate acceptable reproducibility to enable the study of interventions (Roberts *et al.*, 2010). Interestingly, the reliability of the physiological and performances responses to recent squash, tennis and golf protocols have not been reported (Davey *et al.*, 2003; Kingsley *et al.*, 2006; Hayes *et al.*, 2009).

2.5.3 Physiological and Stress Hormonal Responses to Simulated and Championship Taekwondo Combats

Few investigators have examined the physiological responses to simulated Taekwondo combat with the intent of quantifying the energetic requirements of the activity pattern (Bouhlel *et al.*, 2006; Butios & Tasika, 2007). Bouhlel et al. (2006) evaluated the HR and blood lactate responses to performing full-contact combats in a practice setting using experienced national level male competitors. The combats in this investigation were contested across three rounds of three-minutes with a one-minute rest interval separating each round. The activity pattern of these simulated combats elicited near-maximal cardiovascular responses (99% HRmax) and high blood lactate concentrations (10.2 $mmol.l^{-1}$). The physiological responses to this combat simulation corroborate those measured in national level Taekwondo competition (Heller *et al.*, 1998). In contrast, more recent simulations of Taekwondo combat have evoked markedly lower HR (86% HRmax) and blood lactate (3.4 $mmol.l^{-1}$) responses (Butios & Tasika, 2007). Interestingly, these reduced energetic requirements were documented even though both combat simulations exhibited identical combat structures.

The factors that mediate the physiological incongruity between the simulated and championship combats are difficult to quantify effectively from the available information. This may be a function of a number of factors including variation in the competitors' fitness status between the investigations, differences in the activity levels performed in these combats and variation in the 'stress responses' to these combat settings (Pierce *et al.*, 1976; Hoch *et al.*, 1988; Baron *et al.*, 1992; Ferrauti *et al.*, 2001; Haneishi *et al.*, 2007). It is unlikely that variation in the competitors' fitness status is a key factor mediating the physiological incongruity between these combat settings. This presumption is supported by the correspondence in the competitors' physical capabilities (e.g. mean $\dot{V}O_{2max}$ ranging between 54-56 $ml.kg^{-1}.min^{-1}$) between these investigations (Heller *et al.*, 1998; Bouhlel *et al.*, 2006; Butios & Tasika, 2007). Unfortunately, no attempts were made to record the activity profiles in these combat simulations. This oversight makes it difficult to determine whether differences in the physical workload (activity levels) may have contributed to the divergent physiological responses to these simulated and championship combat settings.

There is compelling evidence to support the notion that variation in the stress responses may be a key factor mediating the dissonant physiological responses to these simulated and championship combat settings. For the purpose of this thesis, the 'stress response' constitutes a set of physical and psychological adjustments that the human body makes in response to threat or stress (Goldstein & Kopin, 2008). This concept is also defined as the 'fight or flight' response whereby the rapid activation of the sympathetic-adrenal-medullar (SAM) and the hypothalamic-pituitary-adrenocortical axis (HPA) preserves the internal environment by producing compensatory and anticipatory adjustments that enhance the likelihood of survival (Goldstein & Kopin, 2008). In elite fencers, championship combats have tended to evoke significantly higher plasma cortisol and catecholamine (adrenaline) concentrations than equivalent practice combats (Hoch *et al.*, 1988). The higher hormonal responses in the championship fencing combats were also accompanied by greater HR responses, and plasma lactate and glucose concentrations. The authors advocate that the greater adrenaline concentration, as a consequence of higher emotional strain, may have augmented anaerobic muscular glycolysis and glycogenolysis in this setting (Hoch *et al.*, 1988). As a range of acute psychological stressors may mediate the release of stress hormones (e.g. catecholamines and cortisol) into the circulation (Gerra *et al.*, 2001; Erickson, Drevets & Schulkin, 2003; Goldstein & Kopin, 2008), and this process augments numerous metabolic functions during rest and exercise (Febbraio, Lambert, Starkie, Proietto & Hargreaves, 1998; Watt, Howlett, Febbraio, Spriet & Hargreaves, 2001; Zouhal, Jacob, Delamarche & Gratas-Delamarche, 2008), this concept is highly conceivable. Interestingly, significantly higher plasma cortisol concentrations have also been identified in the moments before (1 to 4 hours) and after (3 minutes post) championship Taekwondo combats than during the equivalent periods of simulated Taekwondo combat (Obminski, 2008). This finding appears to affirm greater stress hormonal responses to championship Taekwondo combats (Ferrauti *et al.*, 2001; Gerra *et al.*, 2001). It is possible, therefore, that the contrasting physiological responses to the simulated and championship Taekwondo combats (Heller *et al.*, 1998; Bouhlel *et al.*, 2006; Butios & Tasika, 2007) may be mediated primarily by differences in the stress hormonal responses to these combat settings. As the precise mechanisms that govern this response remain elusive, there is merit in exploring this phenomenon. Future research should attempt to establish whether the contrasting physiological responses exhibited by the simulated and championship Taekwondo combats in the literature are indeed a function of differences in the stress hormonal responses to these combat settings or a consequence of other factors. This information may have profound implications for the understanding of the physiological demands of this combat sport.

2.6 PHYSIOLOGICAL AND HORMONAL RESPONSES TO PERFORMING REPEATED TAEKWONDO COMBATS

It is clear that information pertaining to the physiological demands of a single Taekwondo combat is incomplete and warrants further investigation. During a Taekwondo event, however, competitors may be required to compete in a number of combats during a single day with varying time intervals separating each match. Few attempts have been made to examine the physiological, hormonal and performance responses to this phenomenon in combat sports (Kraemer *et al.*, 2001; Pilz-Burstein *et al.*, 2010). Kraemer et al. (2001) examined the physiological, hormonal and physical performance responses to performing repeated Wrestling combats during a simulated two-day event. Three Wrestling combats were performed on day one and a further two combats were performed on day two. Combats on day one were separated by four hour rest intervals. Whereas on day two a nine hour rest interval was implemented. Performing repeated Wrestling combats in this format modulated the physiological and hormonal responses, and down regulated a number of physical performance capabilities. More precisely, significant attenuations in grip strength, bear-hug strength and isokinetic knee and elbow (flexion and extension) peak torque were identified across both days (Kraemer *et al.*, 2001). The reductions in these physical performances were accompanied by increased plasma creatine kinase (CK) concentrations. The authors of this investigation advocate that the increased CK concentrations were indirectly indicative of muscle tissue damage during the initial three combats and this tissue disruption contributed to the diminished force production (Kraemer *et al.*, 2001). The repeated Wrestling combats in this study also induced significant elevations in circulating levels of plasma cortisol and attenuations in plasma testosterone. These hormonal responses are indicative of enhanced protein catabolic processes at the muscle tissue level (Kraemer *et al.*, 2001; Judelson *et al.*, 2008). Significant reductions in circulating levels of plasma adrenaline were also identified during the final combat of each day in this investigation (Kraemer *et al.*, 2001). The ability of the adrenal gland to secrete adrenaline is important for high intensity exercise performance and in regulating several metabolic processes (Zouhal *et al.*, 2001; Zouhal *et al.*, 2008). This response may represent some form of adrenal insufficiency, which has been attributed to accumulated fatigue, reduced adrenaline resynthesis in the chromaffin cell of the adrenal medulla, and/or fluid restriction and dehydration over the course of the combats (Kraemer *et al.*, 2001). The precise mechanisms that govern the diminished adrenaline concentrations in this setting remain elusive.

The physiological and hormonal responses to performing repeated Taekwondo combats have been examined in adolescent male competitors. Pilz-Burstein et al. (2010) examined the physiological and hormonal responses to performing repeated Taekwondo combats during a simulated one-day event. During the event, the competitors performed three Taekwondo combats with thirty-minute recovery intervals separating each combat. The combats were structured according to the WTF regulations and comprised three two-minute rounds with one-minute rest between each round. Performing repeated Taekwondo combats in this format resulted in significant attenuations in plasma testosterone, free androgen index, luteinizing hormone (LH), follicle stimulating hormone (FSH) and insulin-like growth factor (IGF-I), and increases in plasma cortisol across the bouts (Pilz-Burstein *et al.*, 2010). These hormonal adjustments speak in favour of enhanced protein catabolic processes as the combats were repeated (Pilz-Burstein *et al.*, 2010). Reduced blood lactate concentrations were also identified in the final combat of the event (Pilz-Burstein *et al.*, 2010). These data demonstrate that performing repeated Taekwondo combats with thirty-minute recovery intervals modulates the physiological and hormonal responses in adolescent competitors. No attempts have been made to quantify the physiological and hormonal responses to performing repeated Taekwondo combats in senior male international level competitors. Competitors' age and gender modulate the physiological and hormonal responses to high intensity exercise (Boisseau & Delamarche, 2000; Zouhal *et al.*, 2008; Pilz-Burstein *et al.*, 2010; Hackney *et al.*, 2011). This would suggest that the available data on male adolescent Taekwondo competitors' may not be generalisable to other populations of Taekwondo competitors. As such, investigations into the physiological and hormonal responses to performing repeated Taekwondo combats in senior male international level competitors would seem necessary.

The recovery interval between each combat may also mediate the physiological and hormonal responses to performing repeated combats. In combat sports such as Judo, for instance, the recovery of a number of plasma metabolites including lactate, non-esterified free fatty acids (NEFA) and glycerol were largely incomplete sixty minutes following combat (Degoutte, Jouanel & Filaire, 2003). The adjustments in a number of these plasma metabolites during Judo combat are similar in magnitude to those in Taekwondo combat (Heller *et al.*, 1998; Bouhlel *et al.*, 2006). As such, shorter recovery intervals between the repeated Taekwondo combats (e.g. $\leq$ 60 minutes), that perturb homeostasis, may modulate the physiological and hormonal responses in the subsequent combats (Tardieu-Berger, Thevenet, Zouhal & Prioux, 2004; Goto, Ishii, Mizuno & Takamatsu, 2007; Bailey, Vanhatalo, Wilkerson, Dimenna & Jones, 2009). In contrast, longer recovery intervals between the repeated Taekwondo combats (e.g. > 60 minutes) may permit more complete restoration of homeostatic control, thereby mitigating the extent of the physiological and hormonal adjustments during successive combats (Bassett, Merrill, Nagle, Agre & Sampedro, 1991; Romijn *et al.*, 1993; Marliss *et al.*, 2000; Sigal *et al.*, 2000; Stokes, Nevill, Frystyk, Lakomy & Hall, 2005; Burnley, Doust & Jones, 2006). The influence of different recovery intervals on the physiological and hormonal responses to performing repeated Taekwondo combats is unknown. Future research should attempt to elucidate whether performing repeated Taekwondo combats influences the physiological and hormonal responses in senior male international competitors and if varying the recovery interval between the combats modulates these responses. This information may serve as a useful ergonomic framework to inform the structure of conditioning practices for competition. It may also assist in the development and selection of recovery interventions in relation to the time interval between successive combats.

2.7 SUMMARY

In summary, a range of methodological approaches have been utilised to study the physiological demands of Taekwondo. These include behavioural observations during competition (e.g. time-motion analysis), physiological evaluations in actual and simulated competition, and the assessment of competitors' physical capabilities. The available data on the physical capabilities of elite Taekwondo competitors' may be associated with the demands of competition (Thompson & Vinueza, 1991; Heller *et al.*, 1998; Toskovic *et al.*, 2004; Markovic *et al.*, 2005; Bouhlel *et al.*, 2006), but it may also reflect competitors' genetic endowment, health status, and the demands of regular training practices as opposed to the less frequent physiological stress of competition (Toskovic *et al.*, 2004; Mohr *et al.*, 2007; Lippi *et al.*, 2009). As a consequence of this limitation, this experimental framework was not implemented to study the physiological demands of Taekwondo in the current thesis.

Collecting physiological measures in authentic competition and training settings constitutes the most ecologically valid approach to study the energetic demands of Taekwondo. A limited number of investigations have examined the physiological responses to championship combats (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). As the available data represent the demands of ITF and STF national level Taekwondo combats, that implement discordant regulations and combat formats, it may be limited in its generalisabilty to WTF international level competition. The aim of study 3.1 was therefore to examine the physiological responses and perceived exertion during WTF international level Taekwondo competition. It was hypothesised that the physiological responses to WTF international level Taekwondo combat would not be generalisable to other styles of Taekwondo combat.

A limited number of investigators have also examined the physiological responses to Taekwondo training (Pieter *et al.*, 1990; Toskovic *et al.*, 2002; Bouhlel *et al.*, 2006). While the available data may provide insights into the physiological demands of specific Taekwondo training activities, it may be criticised on the grounds of ecological validity. These investigations have examined training simulations in laboratory environments, utilising inexperienced participants, and unrealistic work to rest ratios, number of actions, durations and intensities of practice (Pieter *et al.*, 1990; Toskovic *et al.*, 2002; Bouhlel *et al.*, 2006). As such, the available data may provide a disingenuous representation of the demands of conventional Taekwondo training. The aim of study 3.3 was therefore to evaluate the HR responses to specific Taekwondo training activities practiced by experienced practitioners in an ecologically valid training environment. It was hypothesised that ecologically valid Taekwondo training practices would elicit reduced cardiovascular intensities than existing laboratory-based training simulations, and these intensities would be insufficient to prepare competitors' for the cardiovascular demands of competition.

Collecting physiological measures in actual championship events may be ecologically favourable to quantify the acute physiological demands of competition. A number of difficulties have been identified by adopting this experimental approach, such as the constraints of carrying out detailed physiological assessments in this setting and the inability to provide appropriate experimental control of the environment. These issues may limit our understanding of the physiological demands of this combat sport and preclude the efficient study of interventions. A number of alternative approaches may be selected to circumvent these constraints. Making observations during actual competition using time-motion analysis is a favourable research construct. Few investigators have adopted this approach to quantify the energetic requirements of the combat activity (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). As these data were collected from ITF and STF national level combats, that implement divergent regulations and combat formats, it may not be generalisable to WTF international level competition. The available data on the injury profiles of Taekwondo competition also provide circuitous evidence to suggest that the activity profiles may be modulated by a competitor's weight category and the round of combat (Koh *et al.*, 2001; Koh & Watkinson, 2002; Kazemi *et al.*, 2006). No attempts have been made to compare the activity profiles of different weight categories and/or between the rounds of WTF combat with the intent of elucidating the energetic requirements. The aim of study 3.2 was therefore to examine the activity profiles of elite male competitors during WTF international level Taekwondo competition and compare these between selected weight divisions and rounds. It was hypothesised that the activity profile in WTF international level Taekwondo competition would be influenced by a competitor's weight category and the round of combat, and these activity patterns would not be generalisable to other styles of Taekwondo combat.

An alternative experimental framework that may be adopted by researchers to overcome the constraints associated with collecting physiological measures in competition involves the development and use of controlled simulations of competition. These simulations attempt to recreate the activity pattern of actual competition while providing greater control over key experimental variables (Drust *et al.*, 2007). This simulation model may permit more detailed study of the energetic demands of the tournament activity and it may provide a controlled environment to facilitate the study of interventions (Drust *et al.*, 2000; Thompson *et al.*, 2001; Morris *et al.*, 2003; Sunderland, Morris & Nevill, 2008; Roberts *et al.*, 2010). As no attempts have been made to devise an exercise protocol that simulates the activity pattern of Taekwondo combat, this constituted the primary aim of study 4.1. It was hypothesised that the Taekwondo simulation would provide a close approximation of the activity profiles and the physiological responses elicited in championship competition.

A number of investigators have collected physiological measures during full-contact Taekwondo simulations with the intent of quantifying the energetic requirements of the combat activity (Bouhlel *et al.*, 2006; Butios & Tasika, 2007). Some, but not all, of these full-contact simulations demonstrate a tendency to elicit reduced physiological responses in comparison to championship combats (Bouhlel *et al*., 2006; Butios & Tasika, 2007). This physiological incongruity has been ascribed to differences in the competitors' fitness status and activity profiles between the investigations, and/or dissonant stress responses to these combat settings. While a number of causal factors have been proposed, there is compelling evidence to implicate dissonant stress responses as the primary factor mediating the physiological incongruity between the simulated and championship combats (Hoch *et al.*, 1988; Erickson *et al.*, 2003; Obminski, 2008; Chiodo *et al.*, 2009). The aim of study 4.2 was therefore to compare the physiological and stress hormonal responses to performing Taekwondo combats in simulated and championship settings. It was hypothesised that simulated Taekwondo combats would not recreate the physiological responses of championship combats as a consequence of the increased stress responses in competition.

It is clear from the review of literature that information concerning the physiological demands of a single Taekwondo combat is incomplete and necessitates further investigation. During a Taekwondo event, however, competitors' may be required to compete in several combats during a single day interspersed with varied recovery intervals. In adolescent competitors, performing repeated combats interspersed with thirty-minute rest intervals modulates the physiological and hormonal responses to combat. The rest interval between each repeated combat may also mediate the physiological and hormonal responses to combat and influence the recovery of a number of metabolites (Degoutte *et al.*, 2003; Stokes *et al.*, 2005; Burnley *et al.*, 2006; Goto *et al.*, 2007; Bailey *et al.*, 2009). No attempts have been made to examine the physiological and hormonal responses to successive Taekwondo combats using an ecologically valid competition time structure. The aim of study 5.1 was therefore to examine the physiological and hormonal responses to performing successive Taekwondo combats, in senior male competitors, using an ecologically valid competition time structure. It was hypothesised that performing successive Taekwondo combats in an ecologically valid time structure would modulate the physiological and hormonal responses to combat and perturb homeostasis between the combats.

CHAPTER 3

UNDERSTANDING THE FUNDAMENTAL PHYSIOLOGICAL DEMANDS OF TAEKWONDO

3.1 PHYSIOLOGICAL RESPONSES AND PERCEIVED EXERTION DURING INTERNATIONAL TAEKWONDO COMPETITION

3.1.1 Introduction

A limited number of investigations have examined the acute physiological responses to championship Taekwondo competition (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). The available data suggest that the activity pattern of combat induces high demands upon both aerobic and anaerobic metabolism (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). While these data provide important insights into the energetic requirements of the combat activity, they represent the demands of ITF and STF national level events. The physiological and perceived exertion responses to WTF international level Taekwondo competition have never been investigated. There is evidence to suggest that the available data on the acute physiological demands of Taekwondo combat may not be generalisable to different levels of competition (Toskovic *et al.*, 2004; Markovic *et al.*, 2005). The discordant combat formats and regulations implemented in these studies may also limit the generalisability of these data to WTF combats (Bouhlel *et al.*, 2006; Iide *et al.*, 2008; Baudry & Roux, 2009). An evaluation of the physiological and perceived exertion responses to WTF international level Taekwondo competition is, therefore, necessary to inform the structure of conditioning sessions for this population of competitors. The aim of this study was to investigate the physiological responses and perceived exertion during WTF international level Taekwondo competition. It was hypothesised that the physiological responses to WTF international level Taekwondo combat would not be generalisable to other styles of Taekwondo combat.

3.1.2 Methods

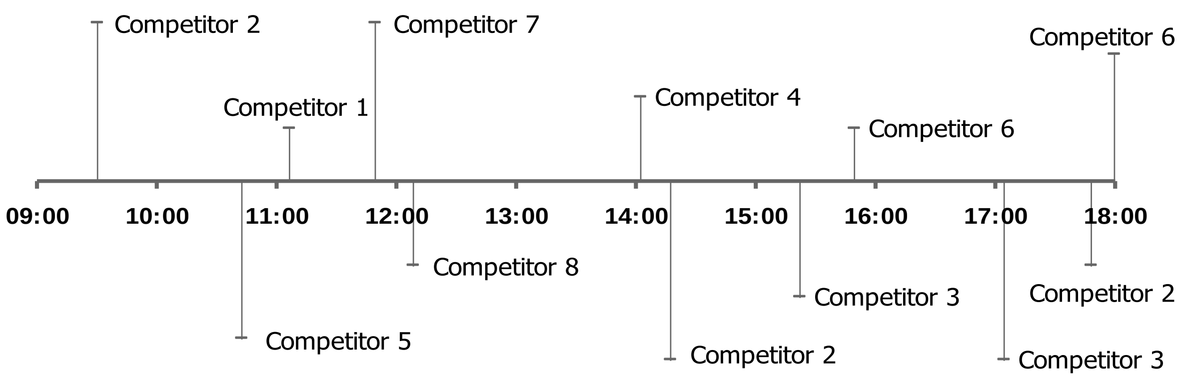
3.1.2.1 Participants

Eight male Taekwondo black belts (mean ± SD, age 22 ± 4 years, body mass 69.4 ± 13.4 kg, height 1.82 ± 0.10 m, competition experience 9 ± 5 years) from the British national team took part in this study. The sample included three 3rd Dan grades, three 2nd Dan grades and two 1st Dan grades. All participants were regularly competing in WTF international events (e.g. European Championship and World Championship events) under different weight categories. More specifically, the current sample comprised one participant from each of the eight standard WTF weight divisions (WTF, 2010). Taekwondo was the only active form of training for these participants, with some general cardiovascular work and resistance training incorporated within these sessions. All participants were actively involved in the same training programme in preparation for the competition event. Participants were informed of the test procedures and potential risks, and informed consent was attained. The project was granted ethical approval in accordance with University Ethics Code of Conduct.

3.1.2.2 Competition Procedures

All participants competed in a WTF sanctioned senior level international competition event (Swedish Open, Trelleborg, Sweden, 2006). The competition was held in a gymnasium on standard mats, and all qualifying, semi-final and final phases of the event occurred between the hours of 9:00 and 19:00 during the same day. The combats included three rounds of two-minutes with 30 s recovery between each round. The data inclusion criteria were the successful attainment of HR, blood lactate and RPE across three rounds of combat. In total, data from twelve combats were successfully recorded in accordance with the inclusion criteria. Thus, the mean data included here represent eight competitors during a total of twelve combats. These data were obtained from combats contested during the qualifying, semi-final and final phases of the competition event. Competitors who were examined on repeated occasions may, therefore, have been exposed to a higher degree of difficulty as the combats progressed during these phases. The structure and start time of the combats that were recorded throughout the competitive day are presented in Figure 3.1.1. Temperature and humidity was recorded next to the competition area at 9:00, 13:00 and 18:00 hours using a whirling psychrometer (G.H. Zeal Ltd, London, UK). Mean $\pm$ SD temperature and relative humidity was 23 $\pm$ 1 ^{o}C, and 38 $\pm$ 6%, respectively.

Figure 3.1.1: Structure and start time of competitors' combats throughout the competitive day.



Time line is presented in 24h format; values represent hours:minutes.

Each competitor’s HR was used to assess the relative cardiovascular strain associated with competition. This methodology was implemented because it is non-invasive and it has been used previously as a reliable index of exercise intensity in a variety of intermittent exercise settings (Bangsbo, 1994; Heller *et al.*, 1998; Bot & Hollander, 2000). Competitors were familiarised with the HR monitors during a number of Taekwondo training activities (e.g. contact sparring) and sessions before they were used in competition. Competitors indicated that these HR monitors did not impede their movements or behaviour in any manner during the Taekwondo activities. In the event, competitors’ HR was recorded at 5 s intervals throughout each combat and during recovery using the Polar Team System (Polar Electro, Kempele, Finland). Each HR transmitter was attached across the participants’ chest under the body armour before each individual combat commenced. Data was subsequently downloaded using Polar Precision Software (Version 4.0, Polar Electro, Kempele, Finland). Mean $\pm$ SD HR was calculated for each round, the 30 s recovery period between each round and for a two-minute period before combat to provide an indication of the cardiovascular strain elicited during these specific periods. The SD of competitors HR was calculated for each round to examine the degree of variation in the cardiovascular demands during the rounds. The HR data were expressed as a percentage of competitors’ predicted HRmax and classified into intensity zones identified by the American College of Sports Medicine (ACSM) (ACSM, 1998). The average percentage of time spent in each of the ACSM HR intensity zones was also calculated for each round. Competitors were unavailable for maximal laboratory testing at the time of data collection; thus HRmax was calculated from the standard equation 220 – age. It appears pertinent to note that during subsequent evaluations the author identified that the mean $\pm$ SD HRmax (n = 8) determined from laboratory based treadmill tests (191 $\pm$ 5 beats·min^{-1}) was lower ($P < 0.001$) than that obtained during both Taekwondo competition (199 $\pm$ 4 beats·min^{-1}) and estimated from the equation 220 – age (199 $\pm$ 4 beats·min^{-1}). Thus, the equation HRmax = 220 - age appears to provide a reasonable estimation of the HRmax in this sample of competitors as opposed to laboratory based determinations.

Whole blood lactate concentrations were measured and used as an indicator of the energy production from anaerobic glycolysis during combats (Gaitanos *et al.*, 1993; Bangsbo, 1994). In this environment, the blood lactate concentration represents the balance between production, release, and removal, and hence should be interpreted cautiously (Bangsbo, 1994). Blood lactate concentrations may reflect, but underestimate, the lactate production in the minutes before sampling during combat (Bangsbo, 1994). Blood lactate was measured approximately one-minute before combat, directly after each round and one-minute after combat (Lactate Pro Meter, Akray, KDK, Japan). Calibration of the device was completed in accordance with the manufacturer’s instructions before sampling at each combat. Following the insertion of each test strip, a ≈ 5 µl blood sample was taken from the fingertip. Competitors were familiarised with these sampling procedures during regular training sessions before they were used in competition. This device was implemented because of its ease of use in the field and its established reliability in the assessment of whole blood lactate (Pyne, Boston, Martin & Logan, 2000). This device has also been validated against well-established blood assay instruments such as the ABL 700 Acid-Base Analyser, the YSI 2300 Stat Analyser and the Accusport Lactate Meter (Pyne *et al.*, 2000).

RPE was used as an additional methodology to describe and monitor exercise intensity (ACSM, 1998). Borg's 6-20 scale was implemented to determine competitors' RPE for each round (Borg, 1998). Competitors were familiarised with the 6-20 scale *a priori* during training. This required the competitors to rate their perception of effort, in juxtaposition to measures of HR and blood lactate, during a range of Taekwondo training activities and physiological loads. During the event, the competitors were instructed to rate their perception of effort for each whole round independently. These perceptions were recorded immediately at the end of combat to prevent interference during competition. Mean $\pm$ SD RPE was calculated for each round and the units were classified in accordance with ACSM's qualitative descriptors (ACSM, 1998).

3.1.2.3 Statistical Analysis

All data were assessed for normality using the Shapiro-Wilks test before analysis. A repeated measures analysis of variance (ANOVA) was performed on all of the dependent variables to identify differences in the intensity across the rounds and recovery between the rounds. Post-hoc analysis included pair-wise comparisons using Tukey's HSD test. Friedman's repeated measures rank test was used to identify differences in the time spent in specific HR intensity zones. Post-hoc analysis included Wilcoxon's matched-pairs signed-ranks tests with Bonferroni adjustment for multiple comparisons. All statistical procedures were performed using SPSS for windows (Version 14.0, SPSS Ltd, Surrey, UK). Significance was set at $P < 0.05$. Descriptive data are expressed as mean $\pm$ SD unless stated otherwise.

3.1.3 Results

The HR, blood lactate and RPE responses to combat are presented in Table 3.1.1. Significant differences in HR ($P < 0.001$), % HRmax ($P < 0.001$), blood lactate ($P < 0.001$) and RPE ($P < 0.001$) were identified across the rounds. Heart rate ($P < 0.001$), % HRmax ($P < 0.001$) and blood lactate ($P < 0.001$) increased significantly from pre-combat to round 1 and remained significantly higher than pre-combat throughout rounds 2 and 3 (Table 3.1.1). No differences in HR ($P = 0.27$), % HRmax ($P = 0.31$) and RPE ($P = 0.18$) were observed between rounds 1 and 2. Blood lactate continued to increase between rounds 1 and 2 ($P < 0.001$). No differences in HR ($P = 0.75$), % HRmax ($P = 0.76$), RPE ($P = 0.10$) and blood lactate ($P = 0.18$) were identified between rounds 2 and 3. However, significant increases in HR ($P = 0.03$), % HRmax ($P = 0.04$), blood lactate ($P < 0.001$) and RPE ($P < 0.001$) were evident between rounds 1 and 3. No differences in the recovery HR's were identified between the rounds ($P = 0.07$).

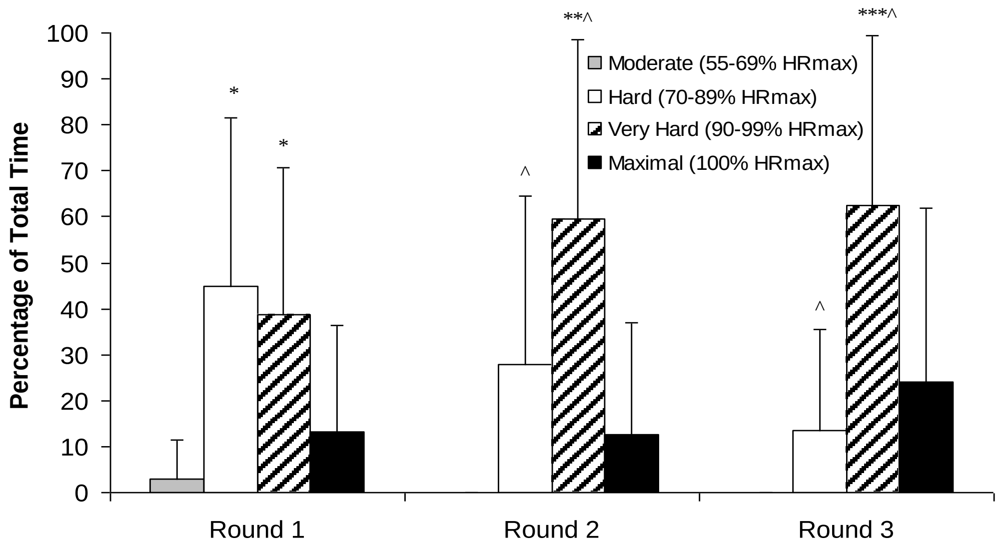
The percentage of time spent in specific HR intensity zones altered significantly between rounds (Figure 3.1.2). A significantly greater proportion of time was spent in 'hard' HR intensities in round 1 than in rounds 2 and 3. Whereas the time spent in 'very hard' HR intensities during round 1 was significantly less than during both rounds 2 and 3. Little variation was evident in competitors' HR during each round. The degree of variation represented by the SD of each round ranged between 4 and 11 beats·min^{-1}, 4 and 7 beats·min^{-1}, and 2 and 7 beats·min^{-1} for rounds 1, 2 and 3, respectively.

Table 3.1.1: Mean ± SD physiological responses and perceived exertion of eight competitors during a total of twelve international combats

	HR (beats·min^{-1})	% HRmax	Recovery HR (beats·min^{-1})	% Recovery HRmax	Blood Lactate (mmol·L^{-1})	RPE (6-20 scale)
Pre-Combat	123 ± 6*	62 ± 3*	-	-	2.7 ± 0.6*	-
Round 1	175 ± 15	89 ± 8	173 ± 15	87 ± 10	7.5 ± 1.6	11 ± 2
Round 2	183 ± 12	93 ± 6	177 ± 13	90 ± 7	10.4 ± 2.4^	13 ± 2
Round 3	187 ± 8^	96 ± 5^	178 ± 12	91 ± 7	11.9 ± 2.1^	14 ± 2^
Mean	182 ± 6	93 ± 3	175 ± 4	89 ± 2	9.9 ± 2.3	13 ± 2

* Denotes pre-combat values are significantly different than reported in rounds 1, 2 and 3 ($P < 0.01$). ^ Denotes corresponding values are significantly different than round 1 ($P < 0.05$).

Figure 3.1.2: Percentage of time spent in heart rate intensity zones across each round



Data represent mean + SD. * Denotes significantly different from moderate intensity in round 1, $P < 0.05$. ** Denotes significantly different from maximum intensity in round 2, $P < 0.05$. *** Denotes significantly different from hard intensity in round 3, $P < 0.05$. ^ Denotes significantly different from corresponding intensity elicited in round 1, $P < 0.05$. Heart rate intensity zones represent the ACSM classifications (ACSM, 1998).

3.1.4 Discussion

To the author's knowledge, this is the first study to detail the physiological responses and perceived exertion during authentic WTF international level Taekwondo competition. The main findings of this study suggest that international Taekwondo competition is a high-intensity activity that elicits near-maximal cardiovascular responses and high blood lactate concentrations, and increases in competitors RPE across combat. In contrast to the hypothesis, the HR and blood lactate responses to WTF international level Taekwondo combat in this study seem to be generalisable to other styles of Taekwondo combat.

The mean HR elicited during international Taekwondo competition was 182 beats·min^{-1}. This corresponded to approximately 93% of competitors' predicted HRmax. These HR responses suggest that high demands are placed upon aerobic metabolism during competition. Comparable cardiovascular strain has been reported during national level Taekwondo competition (≈ 100%

HRmax), simulated Taekwondo competition (99% HRmax), and during analogously structured combat sports tournaments such as Pencak Silat (89 to 97% HRmax) and Karate (97% HRmax) (Imamura *et al.*, 1996; Heller *et al.*, 1998; Aziz *et al.*, 2002; Bouhlel *et al.*, 2006). This would suggest that the physiological demands are similar irrespective of the style of combat or level of competition.

Competitors' HR and % HRmax increased significantly from round 1 to round 3. In addition, the percentage of time spent in 'very hard' HR intensities during rounds 2 and 3 was significantly greater than in round 1. These findings collectively suggest that the cardiovascular demands increased across the rounds. These increased demands could be the result of an increased work rate in response to a greater requirement to obtain points towards the latter stages of combat. The typical duration of combat would suggest that the increased cardiovascular strain is unlikely to be the consequence of physiological mechanisms, such as cardiovascular drift. Competitors' HR demonstrated little variation during each round. This response was evident regardless of the intermittent character of the combat activity (Heller *et al.*, 1998). Similar responses have been reported during both Taekwondo and Pencak Silat competitions using visual inspections of individual competitors HR (Heller *et al.*, 1998; Aziz *et al.*, 2002). The small variation in HR during the rounds may be attributed to the short work:recovery intervals that are experienced during combats (Heller *et al.*, 1998; Aziz *et al.*, 2002; Matsushigue *et al.*, 2009). This would suggest that the physiological demands are sustained throughout the combat, providing the competitors with little time for recovery.

The mean blood lactate concentration elicited during competition was 9.9 $mmol\cdot L^{-1}$. Blood lactate increased significantly from pre-combat to round 1, and between rounds 1 and 2, but not between rounds 2 and 3. The high blood lactate concentrations elicited during each round suggest that high demands are also placed upon anaerobic metabolism during combat, particularly anaerobic glycolysis (Gaitanos *et al.*, 1993). The significant increase in blood lactate from pre-combat to post round 1 would suggest that anaerobic glycolysis was activated during the early stages of combat. Comparable anaerobic demands have been reported during national level Taekwondo competition (11.4 $mmol\cdot L^{-1}$), simulated Taekwondo competition (10.2 $mmol\cdot L^{-1}$) and during analogously structured combat sports tournaments, such as Pencak Silat (8.8 to 12.5 $mmol\cdot L^{-1}$) (Heller *et al.*, 1998; Aziz *et al.*, 2002; Bouhlel *et al.*, 2006). This again would suggest that the type of combat and level of competition do not influence anaerobic energy provision.

The mean RPE elicited during competition was 13 units, corresponding to 'somewhat hard' perceptions of effort (Borg, 1998). The RPE increased significantly from 'light' in round 1 to 'hard' perceptions of effort in round 3. Although RPE increased significantly across the rounds, a clear dissociation between competitors' physiological strain and perception of effort was observed during competition. For instance, the mean competition data demonstrate that high blood lactate concentrations (9.9 mmol·L^{-1}) and 'very hard' HR intensities (93% HRmax) elicited an RPE of 13 units, which is characteristic of 'moderate' physiological loads (e.g. 55 to 69% HRmax) (ACSM, 1998). A clear dissociation between practitioners' cardiovascular strain and RPE has also been observed during Taekwondo training (Toskovic *et al.*, 2002). Ratings of perceived exertion can be affected by numerous physiological and psychological mediators (Noble & Robertson, 1996). This makes it difficult to fully elucidate the cause of the low RPE responses in this setting. A plausible theory is that the competitors' direction of attentional focus may have influenced effort sense in this environment. For instance, increased levels of external attentional focus, such as the addition of memory tasks, mental arithmetic, and audio stimuli during exercise bouts, divert attention away from internal attentional focus (e.g. cardiorespiratory strain) reducing effort sense (Johnson & Siegel, 1987, 1992; Noble & Robertson, 1996; Nethery, 2002; Stanley, Pargman & Tenenbaum, 2007). It is possible that external sensory cues commonly associated with Taekwondo competition, such as tactical decision making in response to an opponent's actions and emotional strain (e.g. anxiety) (Chapman, Lane, Brierley & Terry, 1997), could divert attention away from internal sensory cues, thereby reducing effort sense in this environment. Indeed, the competitors were evaluated during a high level international competition where the consequence of the match outcome was great, and hence the emotional strain and such effects are anticipated to be high. Further research is necessary to substantiate this hypothesis. Irrespective of the mechanisms involved, the findings of this study suggest that the independent use of RPE to determine exercise intensity may underestimate the degree of physiological strain in sports such as Taekwondo.

3.1.5 Conclusions and Practical Applications

International level Taekwondo competition elicited near-maximal cardiovascular responses, high blood lactate concentrations and increases in competitors' RPE across combat. Practically, this suggests that Taekwondo conditioning sessions should include exercise bouts, which sufficiently stimulate both aerobic and anaerobic metabolism. Taekwondo practices incorporating comparable activities and work:recovery intervals as those observed during competition should provide a suitable stimulus for such conditioning purposes. Coaches and practitioners should, however, be cautious of using RPE to monitor physiological load in Taekwondo. The present data not only provide the basis of information required to inform the structure of conditioning sessions for WTF international level competitors, but it also appears to be generalisable to other populations of Taekwondo practitioners.

3.2 TIME-MOTION ANALYSIS OF INTERNATIONAL TAEKWONDO COMPETITION

3.2.1 Introduction

A limited number of investigations have examined the activity profiles of Taekwondo combat with the intent of quantifying its energetic demands (Heller *et al.*, 1998; Matsushigue *et al.*, 2009), and technical and tactical performances (Kazemi *et al.*, 2006; Kazemi *et al.*, 2009). This approach has been implicated more frequently for determining the incidence of injuries in combat (Koh & Watkinson, 2002; Roh & Watkinson, 2002; Koh *et al.*, 2004; Beis *et al.*, 2007). Studies examining the activity profile of combat with the intention of elucidating the energetic demands of the sport are restricted to relatively simplistic evaluations of national level combat (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). The findings of these investigations demonstrate that 3-5 s maximal fighting efforts are interspersed with low intensity non-fighting activity periods at ratios ranging between 1:3 and 1:6 (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). As these data were collected from combats organised under different governing bodies (that implement discordant regulations and combat formats), it may limit their generalisability to WTF competition. As such, a comprehensive appraisal of the activity profiles in WTF Taekwondo combat would seem necessary. The available data on the technical and tactical profiles, and the incidence of injuries in Taekwondo competition, also provide evidence to suggest that the activity profile may be modulated by a competitor's weight category and the round of combat (Koh *et al.*, 2001; Koh & Watkinson, 2002; Kazemi *et al.*, 2006). No attempts have been made to compare the activity levels of different weight categories and/or between the rounds of combat in the context of determining the energetic requirements. The aim of this investigation was to examine the activity profiles of elite male competitors during WTF international level Taekwondo competition and compare these between selected weight divisions and rounds. It was hypothesised that the activity profile in WTF international level Taekwondo competition would be influenced by a competitor's weight category and the round of combat, and these activity patterns would not be generalisabile to other styles of Taekwondo combat.

3.2.2 Methods

3.2.2.1 Experimental Approach

Twelve elite senior male WTF registered Taekwondo competitors equally representing fin, feather, and heavy weight divisions were studied during the semi-final and final stages of the 17th Men's World Taekwondo Championships in Madrid, Spain, 2005. This experimental approach was selected to characterise the activity profile of the most successful competitors competing in one of the most substantial WTF international level competitions (WTF, 2010). The overall activity profile of combat was calculated to permit effective comparisons with existing research (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). This approach allowed the author to examine and demonstrate the variable nature of the combat activity profile, and identify differences in the activity levels between each round. Four competitors from Fin (-54kg), Feather (-67kg), and Heavy (+84kg) weight divisions (WTF, 2010) were examined across one or more combats during the event to determine the activity profiles of these selected weight categories. Only three of the eight standard WTF weight categories were selected for analysis. This choice was a compromise between providing a comprehensive appraisal of the general activity profile and examining whether a competitor's weight category modulates the activity pattern. It was hypothesised that differences, if any, in the activity profiles would be more pronounced between categories that exhibit large differences in competitors' body mass. As such, these specific weight categories were selected to represent a wide range (e.g. lightest, middle and heaviest) of WTF weight divisions. In total, the analysis resulted in eighteen competitor evaluations, comprising six from each individual weight division. This sample size was selected on the basis that it represented all of the competitors that were competing in these weight divisions during the final stages of this specific tournament. This experimental approach also provided suitable control of potential mediating factors, such as competitors' success (Kazemi *et al.*, 2006; Matsushigue *et al.*, 2009), the stage of the tournament and the level of competition, from confounding the analysis. All of the experimental procedures were granted ethical approval in accordance with local University Research Ethics Framework.

3.2.2.2 Development of the Time-motion System

Several combats from the World Championship event were initially examined to identify the typical activities and activity phases. A time-motion system was subsequently developed considering these initial observations (Table 3.2.1). To permit a comprehensive appraisal of the activity profiles, individual activities were recorded and classified in accordance with conventional technical descriptions and terms (Kim *et al.*, 1999; Hornsey, 2002). The time-motion system included a detailed analysis of individual fighting techniques and preparatory actions. This range of actions was included to facilitate the detection of subtle differences in the technical performances (Hughes & Franks, 2004; Hughes & Franks, 2008) and activity levels between the selected weight categories. Both the frequency and duration of activities were noted and assimilated into four independent activity phases: fighting activity, preparatory activity, non-preparatory activity, and stoppage activity (Table 3.2.1). These distinct phases were selected to characterise the different objectives of each movement.

All preparatory activities were performed in a fighting stance (Kim *et al.*, 1999) with the purpose of creating an opening to launch an effective attack (Table 3.2.1). Preparatory time was initiated once the competitor adopted a fighting stance and moved in preparation to attack an opponent. Preparatory time ceased if the competitor moved out of a fighting stance or if a stoppage occurred. Fighting activities were executed during an exchange between competitors with the aim of obtaining and/or preventing a point or technical knockout (Table 3.2.1). Fighting time was initiated with the movement out of a fighting stance into an exchange and ceased once the final execution was complete. More specifically, an execution was complete once the kicking foot was returned to the floor, punching or blocking limb was retracted or when prohibited contact between the competitors ended. Non-preparatory activities were performed in the absence of a fighting stance with the aim of re-establishing a suitable range and position to recommence preparatory activity (Table 3.2.1). Non-preparatory time commenced if an athlete moved out of a fighting stance and ceased once a fighting stance was adopted or if a stoppage occurred. Stoppage time represented the combat periods that were interrupted by particular events. These events comprised general, injury, and penalty stoppages. General stoppages denoted the time required for the referee to separate the opponents after an exchange. Injury stoppages represented periods that competitors were injured or knocked to the ground. Penalty stoppages indicated the time that the referee awarded a penalty to a competitor (Table 3.2.1). Stoppage time was initiated on the referees ‘break’ hand signal (Kim *et al.*, 1999; WTF, 2010) or if a competitor was knocked to the ground. Stoppage time ceased on the referees hand signal to ‘begin’(Kim *et al.*, 1999; WTF, 2010).

3.2.2.3 Time-motion System Reliability

To establish the reliability (Drust *et al.*, 2007) of the time-motion system one observer analysed a selected combat on two occasions, each separated by four days. This combat was re-analysed by the same observer after the analysis of every four combats (≈ every four days) throughout the examination period to determine the systems consistency (Hopkins, 2000). The same combat was also analysed by a second observer, who was familiar with the sport, to establish objectivity (Drust *et al.*, 2007). Cohen’s Kappa statistic (Altman, 1991) was applied to all activities of the system to evaluate the level of agreement between repeated observations (including the frequency and time of actions). Kappa values of 0.41-0.60, 0.61-0.80, and 0.81-1.0 represented moderate, good, and very good agreement respectively (Altman, 1991). Coefficients of variation (CV) (Hopkins, 2000) were calculated for the overall times spent in the specific activity phases and for the fighting:non-fighting ratios. These were derived from each individual activity phase during the combats.

Table 3.2.1: Taekwondo activity classification system

Fighting Activity	Preparatory Activity	Non-preparatory Activity	Stoppage Activity
KICK	**FOOTWORK**	**FOOTWORK**	**STOPPAGE**
Turning Kick*	Stand	Stand	General
Front Kick	Bounce	Active Movement	Injury
Side Kick	Slide#		Penalty
Back Kick	Step		
Push Kick	Turn		
Hook Kick**			
Spinning Hook Kick**	**FEINT**		
Axe Kick***	*(Deceptive movements: hands, legs & body)*		
PUNCH			
BLOCK *(Arms & lifting of the legs)*			
PROHIBITED ACTS *(Holding, pushing & torso-torso contact)*			

* Technique also defined as a Roundhouse Kick; **Technique also defined as a Whip Kick or Spinning Whip Kick; *** Technique also defined as a Chop Kick; # Definition of a slide movement adopted from Kim et al (1999).

The reliability of the time-motion system demonstrated ‘very good’ agreement between repeated trials. Kappa statistics were 0.95, 0.97, 0.96 and 0.97 for re-test trials 1, 2, 3 and 4 respectively. The overall reliability CVs for the fighting, preparatory, non-preparatory and stoppage times, and the fighting:non-fighting ratios were 2.3, 1.4, 2.3, 3.8 and 1.0%, respectively. These statistics suggest that the time-motion system is reliable and suitable for the purpose of this investigation. The objectivity of the system also demonstrated ‘very good’ agreement between the raters (kappa statistic 0.95). The overall objectivity CVs for the fighting, preparatory, non-preparatory and stoppage times, and the fighting:non-fighting ratios were 2.3, 1.7, 3.4, 5.0 and 2.7%, respectively. This suggests that the system can also be used by different researchers to effectively study the activity profile of Taekwondo competition.

3.2.2.4 Data Collection and Reduction

Selected combats from the World Championships were filmed using a digital video recorder (Panasonic DV, 2.1) and the data were stored on mini DV tapes (60/90 ME, DVM60, JVC). Each video recorder was positioned in line with the referees mark outside the field of Taekwondo play (Figure 2.2.1). The camera was set at a standard height of ≈1.5 metres above the contest area to ensure an adequate field of vision from all angles. The data inclusion criterion was the successful recording of both competitors throughout the entire 3 rounds of combat. To control for the confounding influences of competitors success on the activity profile (Kazemi *et al.*, 2006; Matsushigue *et al.*, 2009), the data for each weight category included an equal number of wins (n = 3) and losses (n = 3). Each DV formatted combat was subsequently converted to MPEG using digital video editing software (River Past, Video Cleaner, Version 6.9) and stored on standard data CDs. Each MPEG formatted combat was analysed and the activities were noted across 0.4 s time units (every 10 frames) using the Quintic Player Software (Version 3.09, Quintic Consultancy Ltd, Coventry, UK). The activities were noted across specific time units to maximise the repeatability and efficiency of the time element of the system. As pilot analysis identified that the time taken to complete individual activities was typically 0.4 s to 0.8 s it seemed logical to implement measurement intervals of 0.4 s.

3.2.2.5 Statistical Analysis

The mean $\pm$ SD frequency and duration of activities were calculated for all of the weight categories (including the whole combat and each individual round) and for each individual weight category. The data were assessed for normality using the Shapiro-Wilks test prior to performing inferential statistical analysis. A repeated measures ANOVA was implemented to identify differences in each of the dependent variables across the rounds. A one-way ANOVA was used to identify differences in the dependent variables between the weight categories. Post-hoc analysis included pair-wise comparisons using Bonferroni interval adjustment. Statistical procedures were performed using SPSS for windows (Version 16.0, SPSS, Inc. Chicago, IL). Significance was set at $P < 0.05$ and effect sizes (ES; Cohen's d) were calculated to determine magnitude of the observed difference in relation to the small sample size. Effect size values were considered as trivial (< 0.20), small (0.20 to 0.49), moderate (0.50 to 0.79) and large (> 0.80) in accordance with Cohen's conventional interpretations (Cohen, 1988).

3.2.3 Results

3.2.3.1 Overall Combat Activity Profile

Twelve ± 3% of the total combat time comprised fighting activity, 49 ± 5% preparatory activity, 13 ± 8% non-preparatory activity and 26 ± 14% stoppage activity. The mean overall times for the fighting, preparatory, non-preparatory, and stoppage activities during combat are presented in Table 3.2.2. The majority of the fighting periods (72 ± 16%) lasted ≤ 2 s. These were interspersed with variable non-fighting (including preparatory, non-preparatory, and general stoppages) periods (Figure 3.2.1). Most (70 ± 16%) of the non-fighting periods lasted ≤ 16 s, though half (50 ± 29%) of these periods lasted ≤ 10 s and a substantial proportion (32 ± 20%) lasted ≤ 6 s. These durations resulted in an average fighting to non-fighting ratio of 1:6. The overall frequency of fighting, preparatory, non-preparatory, and stoppage activities performed during combat are presented in Tables 3.2.3 and 3.2.4.

Table 3.2.2: Mean ± SD duration and frequency of activities between the weight categories

Activity Phase	Fin -54kg	Feather -67kg	Heavy +84kg	Overall
Fighting Activity (s)	1.4 ± 0.2	1.6 ± 0.2	1.8 ± 0.3^	1.7 ± 0.3
Preparatory Activity (s)	5.3 ± 1.0	8.2 ± 2.6^	5.8 ± 1.1**	6.4 ± 2.1
Non Preparatory Activity (s)	3.4 ± 1.2	2.7 ± 0.7	2.9 ± 0.6	3.0 ± 0.6
General Stoppage Activity (s)	2.9 ± 0.8	3.4 ± 0.9	3.0 ± 0.8	2.8 ± 0.9
Fighting:Non-fighting Ratio (1:x)	6.4 ± 1.2	7.0 ± 3.2	5.5 ± 0.8	6.3 ± 2.0
Number of Exchanges	29 ± 3	24 ± 6	32 ± 5*	28 ± 6
Number of Kicks	32 ± 8	29 ± 7	33 ± 6	31 ± 7

^ Denotes significantly different from fin weight, $P < 0.05$
* Denotes significantly different from feather weight, $P < 0.05$
** Denotes a trend for differences in comparison to feather weight, $P = 0.07$

Figure 3.2.1: Mean ± SD overall frequency of fighting and non-fighting periods during eighteen competitor evaluations

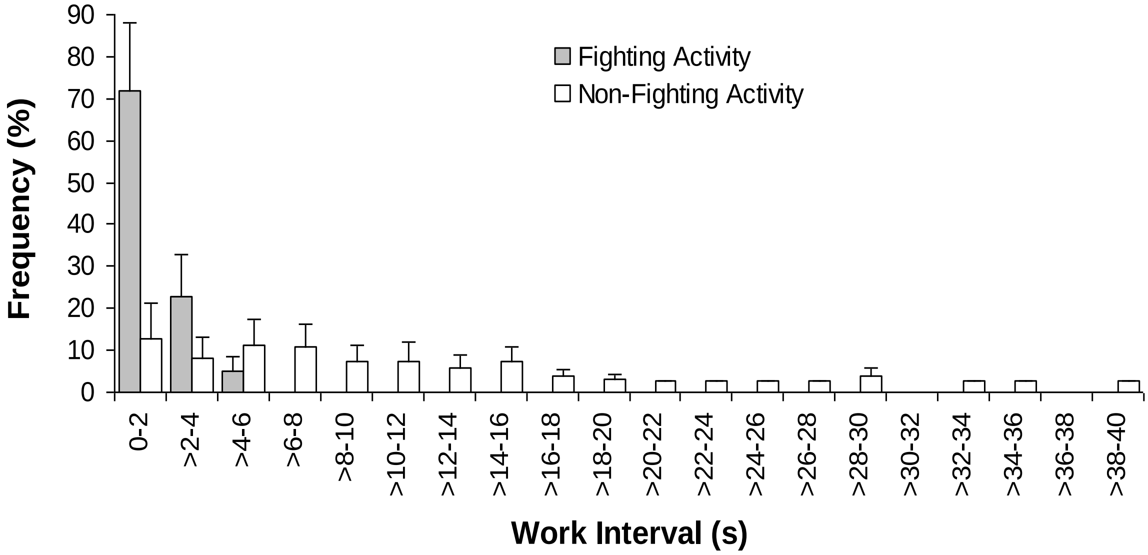


Table 3.2.3: Mean ± SD frequency of fighting activities between the weight categories

Fighting Activity	Fin -54kg	Feather -67kg	Heavy +84kg	Overall
Turning Kick	29 ± 4	28 ± 6	30 ± 6	29 ± 5
Front Kick	4 ± 4	1 ± 0	2 ± 1	2 ± 2
Side Kick	1 ± 0	1 ± 0	1 ± 0	1 ± 0
Back Kick	2 ± 1	3 ± 1	3 ± 0	2 ± 1
Push Kick	2 ± 1	1 ± 0	1 ± 0	1 ± 1
Hook Kick	0	0	0	0
Spinning Hook Kick	2 ± 1	0	1 ± 0	1 ± 1
Axe Kick	1 ± 0	0	2 ± 1	1 ± 1
Punch	1 ± 0*	2 ± 1	2 ± 2	2 ± 1
Block	4 ± 2	3 ± 4	8 ± 6	5 ± 5
Prohibited Acts	10 ± 4	11 ± 5	19 ± 8*^	13 ± 7
Total	56 ± 9	50 ± 9	69 ± 10	57 ± 13

* Denotes significantly different from feather, $P < 0.05$
^ Denotes significantly different from fin, $P < 0.05$

Table 3.2.4: Mean ± SD total frequency and duration of non-fighting activities between the weight categories

Non-fighting Activity Phase	Fin -54kg (n)	Feather -67kg (n)	Heavy +84kg (n)	Overall (n)	Fin -54kg (s)	Feather -67kg (s)	Heavy +84kg (s)	Overall (s)
Preparatory Activity								
Stand	15 ± 7	8 ± 6	17 ± 11	13 ± 9	8.0 ± 4.5	4.9 ± 2.7	11.5 ± 8.2	8.1 ± 6.0
Bounce	196 ± 103	215 ± 120	189 ± 55	200 ± 91	71.3 ± 33.1	84.2 ± 45.4	75.7 ± 22.2	77.1 ± 33.2
Slide	97 ± 48	75 ± 26	70 ± 22	81 ± 35	39.1 ± 19.3	30.7 ± 10.6	29.7 ± 7.3	33.2 ± 13.3
Step	106 ± 39	105 ± 90	128 ± 59	113 ± 63	40.9 ± 13.9	42.0 ± 36.2	50.4 ± 23.8	44.4 ± 25.1
Turn	9 ± 5*	2 ± 2	4 ± 4	6 ± 5	5.5 ± 2.5*	1.2 ± 0.7	2.3 ± 1.6^	3.1 ± 2.8
Feint	30 ± 23*	86 ± 30	54 ± 9	56 ± 32	13.2 ± 10.6*	36.9 ± 14.4	24.0 ± 5.5	24.7 ± 14.2
Total	452 ± 74	490 ± 25	461 ± 32	469 ± 49	178.1 ± 22.5*	200.0 ± 9.5	193.0 ± 13.7	190.6 ± 17.7
Non-Preparatory Activity								
Stand	2 ± 1	1 ± 0	1 ± 0	1 ± 1	1.0 ± 0.3	1.2 ± 0	0.8 ± 0	1.0 ± 0.2
Active Movement	27 ± 6*	10 ± 3	21 ± 9*	19 ± 9	73.3 ± 26.3*	24.2 ± 8.3	51.9 ± 26.1	49.8 ± 29.2
Total	29 ± 7*	11 ± 3	22 ± 9*	20 ± 10	74.3 ± 26.7*	25.4 ± 8.1	52.7 ± 26.0	50.8 ± 29.3
Stoppage Activity								
General	6 ± 2	4 ± 1	13 ± 6*^	8 ± 5	12.0 ± 1.8	14.4 ± 4.4	44.4 ± 26.3*^	23.6 ± 21.0
Injury	6 ± 3	5 ± 2	4 ± 2	5 ± 3	30.3 ± 25.5	38.1 ± 17.4	19.3 ± 2.6	30.5 ± 19.4
Penalty	8 ± 4	5 ± 2	5 ± 4	6 ± 3	40.9 ± 21.4	41.6 ± 4.5	60.9 ± 68.2	47.8 ± 40.0
Total	20 ± 8	14 ± 3	22 ± 6	19 ± 6	83.3 ± 45.6	94.1 ± 18.0	124.6 ± 81.8	101.9 ± 53.9

* Denotes significantly different from feather, $P < 0.05$
^ Denotes significantly different from fin, $P < 0.05$

The mean activity phase data for each round of combat are presented in Table 3.2.5. Preparatory activity time decreased between rounds 1 and 3 (P < 0.001; ES = 0.94). The fighting:non-fighting ratio decreased between rounds 1 and 2 (P = 0.04; ES = 0.75), and between rounds 1 and 3 (P = 0.01; ES = 0.87). No differences in the mean fighting (P = 0.96), non-preparatory (P = 0.10) and general stoppage times (P = 0.10) were identified between the rounds. The total number of exchanges increased between rounds 1 and 3 (P < 0.001; ES = 1.18). The number of kicks increased between rounds 1 and 3 (P < 0.001; ES = 1.25), and rounds 2 and 3 (P = 0.04; ES = 0.85).

Table 3.2.5: Mean ± SD duration and frequency of activities across the rounds for all weight groupings

Activity Phase	Round 1	Round 2	Round 3
Fighting Activity (s)	1.7 ± 0.4	1.7 ± 0.4	1.7 ± 0.5
Preparatory Activity (s)	9.7 ± 5.7	7.0 ± 1.7	5.7 ± 2.0*
Non Preparatory Activity (s)	3.3 ± 1.2	2.9 ± 0.8	2.8 ± 0.9
General Stoppage Activity (s)	2.0 ± 1.9	3.0 ± 0.9	2.9 ± 0.9
Fighting:Non-fighting Ratio (1:x)	7.8 ± 4.2	5.5 ± 1.2*	4.9 ± 2.1*
Number of Exchanges	8 ± 3	9 ± 2	11 ± 2*
Number of Kicks	8 ± 4	10 ± 3	13 ± 4*^

* Denotes significantly different from round 1, P < 0.05
^ Denotes significantly different from round 2, P < 0.05

3.2.3.2 Activity Times between Weight Categories

The mean and total activity phase times for each weight category are presented in Tables 3.2.2 and 3.2.4 respectively. The mean fighting time for heavy weights was significantly greater than for fin weights (P = 0.03; ES = 1.57; Table 3.2.2). Feather weights performed preparatory activities for longer periods than fin weights (P = 0.03; ES = 1.47) and these durations tended to be greater than in the heavy weight division (P = 0.07; ES = 1.20). No differences in the mean non-preparatory times (P = 0.18), general stoppage times (P = 0.16) and fighting:non-fighting ratios (P = 0.49) were identified between the weight categories (Table 3.2.2). Detailed analysis of the total preparatory phase identified differences in the total turning (P < 0.001; ES = 2.34), feinting (P = 0.01; ES = 1.87) and preparatory activity times (P = 0.04; ES = 1.26) between fin and feather weights (Table 3.2.4). During the non-preparatory phase, fin weights spent greater total time engaged in active movements (P < 0.001; ES = 2.51) and consequently greater total time executing non-preparatory activities (P < 0.001; ES = 1.92) than feather weights (Table 3.2.4). Heavy weights spent greater total time engaged in general stoppages than both fin (P = 0.01; ES = 1.73) and feather (P = 0.01; ES = 1.59) weights (Table 3.2.4). The frequency of fighting and non-fighting periods was also examined. The mean frequency of 0-2 s fighting intervals performed by feather weights (17 $\pm$ 4) was significantly lower than performed by both fin (24 $\pm$ 3; P = 0.02; ES = 1.98) and heavy (22 $\pm$ 5; P = 0.04; ES = 1.10) weights. The mean frequency of fighting intervals lasting >2-4 s was greater for heavy (9 $\pm$ 1) weights than fin (4 $\pm$ 2) weights (P = 0.01; ES = 3.16). No differences in the frequency of the remaining fighting and non-fighting intervals were evident between the weight categories (P > 0.05).

3.2.3.3 Activity Frequencies between Weight Categories

The frequency of fighting, preparatory, non-preparatory, and stoppage activities for each weight category are presented in Tables 3.2.2, 3.2.3 and 3.2.4. During fighting periods, heavy weights were involved in a greater number of prohibited acts than both fin (P = 0.02; ES = 1.42) and feather (P = 0.04; ES = 1.19) weights (Table 3.2.3), and they performed a greater number of exchanges (P = 0.03; ES = 1.44) than feather weights (Table 3.2.2). In the preparatory phase, differences in the total number of turning (P = 0.01; ES = 1.83) and feinting (P < 0.001; ES = 2.09) actions were evident between fin and feather weights (Table 3.2.4). During the non-preparatory period, feather weights were involved in less active movements (P < 0.001; ES = 3.56 and P = 0.03; ES = 1.64) and less total non-preparatory actions (P < 0.001; ES = 3.34 and P = 0.04; ES = 1.64) than both fin and heavy weights respectively (Table 3.2.4). Heavy weights were involved in a greater number of general stoppages than both fin (P = 0.01; ES = 1.56) and feather (P < 0.001; ES = 2.09) weights (Table 3.2.4).

3.2.4 Discussion

This study is the first to provide a comprehensive appraisal of the activity profile in WTF international level Taekwondo competition and to compare these between selected weight divisions and rounds. In agreement with the hypothesis, the activity profiles were modulated by a competitor's weight category and the round of combat, and they were distinguished from other styles of Taekwondo combat. These findings suggest, for the first time, that conditioning sessions may need to be specialised to the requirements of specific weight categories and different styles of Taekwondo combat.

3.2.4.1 Overall Combat Activity Profile

The overall combat data presented in this study characterise the intermittent activity pattern of international level Taekwondo competition. On average 1.7 s of fighting was typically interspersed with 6.4 s of preparatory activity, 3.0 s of non-preparatory activity and 2.8 s of stoppage activity. These periods resulted in an average fighting to non-fighting ratio of 1:6. For the first time, the examination of the frequency of these periods characterise the inherent variability of the fighting and non-fighting periods during combat (Figure 3.2.1). These data provide a valuable ergonomic framework to inform the structure of conditioning sessions for WTF international competition.

The mean fighting to non-fighting ratio in the present study compares favourably with the ratio reported in a recent study of STF national level combat (Matsushigue *et al.*, 2009), yet it is larger than the ratio reported in an earlier study examining ITF national level combat (Heller *et al.*, 1998). The overall frequency of fighting activities performed during combat in the present study was typically higher than the equivalent number of techniques executed in STF national level combat (Matsushigue *et al.*, 2009). This finding would suggest greater overall fighting demands in the current study, which may be a function of the different competition levels and/or variation in the combat structure between these studies. During the STF event, for instance, a single two-minute round of combat was contested in a 5.5 x 5.5 m area after performing both poomse and weapons stages (Matsushigue *et al.*, 2009). In contrast, the combats performed in the ITF event were contested in a 9 x 9 m area and comprised two rounds of two-minutes with a one-minute rest interval separating each round (Heller *et al.*, 1998). These combat formats and the scoring systems are markedly different than the 2005 WTF regulated combats (WTF, 2010). As such, these different fighting demands suggest that the structure of conditioning practices may need to be tailored to the requirements of the specific level of competition and/or style of combat.

Examination of the data across the rounds revealed that the activity profile was modulated by the stage of combat. Significant reductions in the preparatory time and fighting to non-fighting ratios, and an increase in the number of exchanges and kicks across the rounds of combat suggest an increase in the activity of the competitors. Previous research has identified a higher incidence of scoring in round 1 than in rounds 2 and 3 in male Olympic WTF combats (Kazemi *et al.*, 2006). As the total number of kicks performed in the Olympic WTF combats was not reported (Kazemi *et al.*, 2006), it is difficult to quantify whether this incongruity is a function of variations in the activity levels or technique efficacy between the studies. In the context of quantifying the energetic demands, the physiological responses to Taekwondo-specific exercise (Bouhlel *et al.*, 2006) and other combat sport activities (Iide *et al.*, 2008; Baudry & Roux, 2009) are sensitive to changes in both the work and rest intervals. As such, it seems logical to deduce that the increased activity levels across the rounds of combat may increase the energetic requirements (Chapter 3.1). The specific changes in activity identified across the rounds in the present study may be considered to manipulate the activity levels of combat-specific conditioning practices.

3.2.4.2 Activity Profile between Weight Categories

The activity profile of combat was also modulated by a competitor's weight category. Heavy weights performed fighting activity for longer periods than fin weights. This finding appears to be the consequence of heavy weights performing more frequent prohibited acts during each exchange as opposed to the execution of a greater number of exchanges or kicks. Heavy weights also performed a greater number of prohibited acts than feather weights. In contrast, previous research examining the injury profile in WTF regulated combats has identified marked differences in the number of high section kicking techniques performed between these weight divisions (Koh & Watkinson, 2002), but the total number of kicks (including both high and mid section) was not documented. Variation in the number of scoring kicking techniques performed in combat has also been identified between the Olympic WTF weight divisions (Kazemi *et al.*, 2009), but the total number of kicks (including both scoring and non-scoring techniques) was not reported. The greater frequency of prohibited acts performed by heavy weights in the present study appears to result in corresponding increases in the number of general stoppages after each exchange. The greater incidence of prohibited acts, which include actions such as holding, pushing and torso-torso contact suggest that heavy weights are subjected to greater fighting demands during combat. These additional energy requirements are the consequence of movements that characteristically involve concentric and isometric actions of the upper and lower body musculature (Kraemer *et al.*, 2001). As such, heavy weight competitors may require specialised conditioning practices that incorporate more frequent prohibited acts during fighting exchanges to withstand the additional demands imposed by these activities during combat.

Feather weights performed preparatory activity for longer periods than both fin and heavy weights. This finding could be attributed to feather weights executing fewer exchanges during combat, but the number of exchanges performed by the feather weights was only significantly lower than performed in the heavy weight division. It is therefore conceivable that this is also a function of the feather weights performing fewer active movements in the non-preparatory phase (Table 3.2.4). The data therefore indicate that feather weights sustain preparatory activity for longer periods than fin and heavy weights with fewer interruptions from fighting exchanges and non-preparatory actions. This suggests that feather weights typically experience greater demands from preparatory periods during combat, and the infrequent non-preparatory actions indicate that these competitors have fewer intermissions to recover from the demands of both preparatory and fighting actions. As such, feather weight competitors may require specialised conditioning sessions that incorporate longer preparatory periods and infrequent non-preparatory actions to prepare for the additional demands imposed by these activity periods during combat. Although feather weights performed fewer exchanges than heavy weights, the total number of kicks was similar. This suggests that feather weights typically executed a greater quantity of kicks during each fighting exchange. This finding therefore highlights the particular relevance of kick combinations and less frequent exchanges for feather weights conditioning practices.

3.2.5 Conclusions and Practical Applications

The main findings of this study demonstrate that the activity profile in international Taekwondo competition was modulated by competitors' weight category. Most notably, the data highlight the predominance of fighting activity for heavy weights, and preparatory activity and less frequent fighting exchanges for feather weights. These data provide a valuable ergonomic framework to inform the structure of conditioning sessions for WTF Taekwondo competition and suggest, for the first time, that conditioning sessions may need to be specialised to the requirements of specific weight divisions. Adopting such strategies for other styles of Taekwondo combat that implement discordant regulations may require further evidence. Conditioning for WTF competition may need to consider the requirements of a number of situational factors. As such, the impact that specific factors in WTF Taekwondo may have on the combat activity profile warrants further investigation.

3.3 HEART RATE RESPONSES TO CONVENTIONAL TAEKWONDO TRAINING

3.3.1 Introduction

Few investigators have examined the physiological responses to Taekwondo training (Pieter *et al.*, 1990; Toskovic *et al.*, 2002; Bouhlel *et al.*, 2006). The available data suggest that the practice of forms, technical combinations and continuous kicking techniques mediate a range of cardiovascular intensities (Pieter *et al.*, 1990; ACSM, 1998; Toskovic *et al.*, 2002; Bouhlel *et al.*, 2006). A number of these training modes seem to elicit suitable intensities for developing and maintaining cardiovascular fitness for competition (Chapter 3.1) (Heller *et al.*, 1998). While these data provide valuable insights into the cardiovascular requirements of specific Taekwondo training activities, it may be criticised on the grounds of ecological validity. These investigations have examined training simulations in laboratory environments, utilising inexperienced participants, and unrealistic work to rest ratios, number of actions, durations and intensities of practice (Pieter *et al.*, 1990; Toskovic *et al.*, 2002; Bouhlel *et al.*, 2006). The available Taekwondo training data may, therefore, provide a disingenuous representation of the cardiovascular responses to conventional Taekwondo training performed in an ecologically valid setting. To conform to the requirements of ecological validity, future investigations should incorporate field assessments, and utilise realistic work to rest ratios, number of actions, intensities and durations of practice. The structure and proportion of activities within typical training environments should also be taken into consideration. The aim of this study was to evaluate the HR responses of specific Taekwondo training activities practiced by experienced practitioners in an ecologically valid training environment. It was hypothesised that ecologically valid Taekwondo training practices would elicit reduced cardiovascular intensities than existing laboratory-based training simulations, and these intensities may therefore be insufficient to prepare competitors' for the cardiovascular demands of competition.

3.3.2. Methods

3.3.2.1 Experimental Approach

To evaluate the cardiovascular responses of conventional Taekwondo activities, practiced in an ecologically valid setting, HR measures were recorded during a typical Taekwondo training camp.

To enhance the ecological validity of the measurements, the data were recorded from a number of different sessions across the training camp. Although Taekwondo training can be highly variable, the same eight fundamental activities are universally practiced in Taekwondo (Kim *et al.*, 1999; Whang *et al.*, 1999; Hornsey, 2002; ITF, 2006; WTF, 2010). The HR responses from the entire training camp were assimilated into these eight fundamental training activities. This enabled the author to investigate whether conventional training activities elicit HR to within recognised cardiovascular training zones (ACSM, 1998), to identify the relative exercise intensities elicited by each activity and to specify each activities suitability for competition conditioning. This information will be valuable to inform the structure of conditioning sessions for competition. Heart rate is a non-invasive measure that has been frequently used as a reliable index of exercise intensity in a variety of intermittent training and competition settings (Pieter *et al.*, 1990; Bergeron *et al.*, 1991; Bangsbo, 1994; Heller *et al.*, 1998). Furthermore, Polar heart rate monitors have been validated against electrocardiogram (ECG) across a range of exercise intensities (Achten & Jeukendrup, 2003).

To further ensure ecological validity, two highly experienced (> 35 years of practice each) international coaches (4th Dan Black Belt) with a WTF refereeing certification (at national and international levels for both poomsae and kyorugi) delivered the training sessions. All of the techniques were practiced on the coaches' command, and the sessions were not manipulated by the researcher in any manner in an attempt to obtain realistic work to rest ratios, durations and intensities of practice. Taking an ecologically valid approach to HR assessment also ensured that the structure and proportion of activities within typical training environments were evaluated in this study. This enabled the author to identify whether the total duration of activity practices during each session satisfied the recommended guidelines for improving and maintaining cardiovascular fitness (ACSM, 1998). The rationale for the inclusion of a homogenous sample of experienced competitors was based on the premise that experienced athletes may have improved economy of movement (Morgan *et al.*, 1995; Jones & Unnithan, 1998). Consequently, experienced and trained athletes are able to work at a lower relative intensity (HR) to produce the same work output (Bransford & Howley, 1977; Morgan *et al.*, 1995; Jones & Unnithan, 1998), and it is these athletes who regularly engage in competition-specific training.

3.3.2.2 Participants

Eight male Taekwondo competitors with 3 to 13 years experience (5.4 ± 3.2 years), including five Dan grades ranging from 4th to 1st Dan, two 1st Keup grades, and one 3rd Keup grade took part in the study. Six of the eight participants were regularly competing in Kyorugi, forms or a combination of both at WTF national (e.g. several medallists at French Championships) and international (e.g. two silver medals at World Championships) events. The participants' typical training regimen before the training camp included set training sessions three times per week, lasting approximately two hours in duration, often with the inclusion of further sessions of personalised work as necessary (range, 6 to 10 hours per week). At flexible intervals in the training calendar the participants were required to attend specific training camps. In this case, the training camp took place across five days and included two daily sessions. Taekwondo training was the only active form of specific training for these participants, with some general light cardiovascular and strength work incorporated within these sessions. Participants mean $\pm$ SD age, mass, and height were 22.5 $\pm$ 4.1 years, 70.5 $\pm$ 15.8 kg, and 1.77 $\pm$ 0.10 m, respectively. All of the experimental procedures were granted ethical approval in accordance with local University Research Ethics Framework. All of the participants were informed of the test procedures and potential risks, and informed consent was attained.

3.3.2.3 Procedures

The participants took part in a five-day Taekwondo training camp that comprised two daily sessions. The goal of the training camp was to satisfy the technical, tactical and physical (e.g. strength, power, speed and competition-specific conditioning) demands of Taekwondo competition. Daily training typically included a morning (≈ 06:30 to 08:00 hours) and evening session (≈ 16:00 to 18:00 hours), with approximately eight hours separating each session. Continuous HR measures were taken during four evening sessions and two morning sessions using the Polar Team System (Polar Electro, Kempele, Finland). The structure of the recorded training activities is presented in figure 3.3.1. In total, 570 minutes of HR data were successfully recorded, and each training session was observed and notated, and a diary of activities was recorded. The HR data were subsequently downloaded using Polar Precision Software (Version 4.0) and mean HRs were calculated for the eight fundamental Taekwondo training activities. The descriptive HR data were also expressed as a percentage of the participants' age predicted HRmax. As the participants were unavailable for maximal laboratory testing at the time of the investigation, HRmax was estimated using the standard equation of 220 - age.

Figure 3.3.1: Structure of recorded training activities

Session 1: 5th August PM

W4 → BF26 → B6 → TC5 → B5 → SD15 → B4 → SD15 → B5 → FS6

Session 2: 6th August AM

WS28 → J19 → S5 → B9 → E26

Session 3: 6th August PM

W4 → TC22 → B4 → SS40 → B4 → P35 → B5 → E11

Session 4: 7th August AM

W10 → J27 → B4 → E43

Session 5: 7th August PM

W17 → F20 → B2 → P11 → B4 → P11 → B2 → P7 → B3 → P8 →

B13 → E18 → B3 → E7

Session 6: 8th August PM

W2 → P11 → B2 → P9 → B7 → FS1 → B1 → FS2 → B1 → FS3 →

B5 → FS3 → B1 → FS3 → B1 → FS3

Notes: numbers represent training time in minutes, letters represent each activity. W=Warm up, B=Break, J=Jog, S=Stretch, E=Elastics, SS=Step Sparring, TC=Technical Combinations, P=Pad Work, F=Forms, BF=Basic Technique and Forms, SD=Sparring drills, FS=Free Sparring

3.3.2.4 Recorded Training Activity Categories

Taekwondo training sessions typically include a combination of the following conventional activities: basic techniques, technical combinations, predetermined sequences of movement (forms), breaking techniques, self-defence techniques, step sparring, sparring drills and free sparring (Kim *et al.*, 1999; Whang *et al.*, 1999; Hornsey, 2002; ITF, 2006; WTF, 2010). During the training sessions, the author notated when each of these individual activities were practiced and a diary of activities was created. During the sessions, breaking techniques and self-defence techniques were not practiced, and hence these categories are omitted from results section. In a number of these sessions, basic techniques and technical combinations were performed on pads, and using elastic stretch bands to provide additional resistance. As such, these activities were categorised as either ‘elastics’ or ‘pad work’. In one session, basic techniques were practiced interchangeably with forms, and hence this activity was categorised as ‘basic techniques and forms’. Consequently, the following eight activity categories were included for analysis: basic techniques and forms, technical combinations, forms, step sparring, sparring drills, free sparring, elastics, and pad work (See Table 2.2.5 [Chapter 2] for the definition of each recorded training activity).

3.3.2.5 Statistical Analysis

A repeated measures ANOVA was performed on the HR data to identify differences in the cardiovascular intensities between the different Taekwondo activities. Post-hoc analysis included pair-wise comparisons using Bonferroni interval adjustment. Significance was set at $P < 0.05$ and the observed power and effect size for the number of subjects ($n = 8$) was 0.95 and 0.83 respectively. Descriptive data are expressed as mean ± SD. All statistical procedures were performed using SPSS for windows (Version 11.5; SPSS, Inc., Chicago, IL).

3.3.3 Results

Taekwondo training elicited mean HRs into 65-81% of practitioners HRmax, and different activities mediated diverse cardiovascular requirements (Table 3.3.1). The practice of elastics, technical combinations and step sparring elicited similar mean HR responses ($P > 0.05$). The mean HR responses produced by these activities were lower ($P < 0.05$) than elicited by the other five activity practices (Table 3.3.1). Pad work elicited greater ($P < 0.05$) mean HR responses than elastics, technical combinations and step sparring. However, pad work elicited lower ($P < 0.05$) mean HR responses than forms, basic technique and forms, sparring drills, and free sparring. The practice of forms, basic technique and forms, sparring drills, and free sparring evoked similar cardiovascular demands ($P > 0.05$), and these were greater ($P < 0.05$) than the remaining activity practices. No differences in the mean HR responses were identified between the free sparring modes ($P > 0.05$).

Table 3.3.1 Heart rate responses and typical duration of Taekwondo training activities during the training camp (data are mean $\pm$ SD unless stated otherwise)

Taekwondo Activity	HR (beats.min^{-1})	%HRmax^{H}	Relative Exercise Intensity^{R}	Total Duration Over Camp (Minutes)	% Total Time	Duration Over Each Session (Minutes)^{D}
Elastics	128 $\pm$ 13*	65 $\pm$ 6	Moderate	105	18.6	11-43
Step Sparring	133 $\pm$ 16*	67 $\pm$ 10	Moderate	40	7.1	40
Technical Combinations	137 $\pm$ 18*	70 $\pm$ 8	Moderate	27	4.8	5-27
Pad Work	148 $\pm$ 15$^{>}$	75 $\pm$ 8	Hard	91	16.1	20-36
Forms	157 $\pm$ 19$^{\#}$	80 $\pm$ 9	Hard	20	3.5	20
Basic techniques and forms	158 $\pm$ 24$^{\#}$	80 $\pm$ 11	Hard	26	4.6	26
Sparring Drills	160 $\pm$ 17$^{\#}$	81 $\pm$ 9	Hard	30	5.3	30
Free Sparring	161 $\pm$ 15$^{\#}$	81 $\pm$ 7	Hard	21	3.7	6-15
Entire Training Camp	148 $\pm$ 13^{N}	75 $\pm$ 7	Hard	360^{S}	63.6$^{S\ T}$	-

PTO for Table Caption

Table 3.3.1 Caption

* No significant difference in mean HR between these activities ($P > 0.05$), though these activities elicited significantly lower mean HR than the remaining activities ($P < 0.05$)

> Mean HR significantly higher ($P < 0.05$) than elastics, step sparring and technical combinations, but significantly lower ($P < 0.05$) than forms, basic technique and forms, sparing drills and free sparring

\# No significant difference in mean HR between these activities ($P > 0.05$), though these activities elicited significantly higher mean HR than the remaining activities ($P < 0.05$)

N Data not included in statistical analysis

S Data are the sum of the above values

T Remainder of total time comprised of breaks (16.6%), warm up (10.7%) and light intensity running (8.9%)

H %HRmax calculated with equation 220 - age

R Relative exercise intensity based on %HRmax upon physical activity lasting up to 60 minutes (ACSM, 1998)

D Data are range the of times practice during individual sessions

In each of the six recorded training sessions the accumulated duration of the activity practices seemed to be sufficient to promote cardiovascular training adaptations (26-108 minutes). In contrast, the duration of individual activity practices during each session was often below the minimum twenty-minute duration recommended for eliciting cardiovascular training adaptations (ACSM, 1998) (Table 3.3.1). Mean session HRs were within the recognised intensity range for cardiovascular conditioning (120 ± 10 to 169 ± 11 beats.min^{-1}). One of the training sessions did elicit an average HR at the lower end of the intensity threshold (120 ± 10 beats.min^{-1}, 55-65% HRmax), whereas the remaining sessions were well within the recommended guidelines (135 ± 11 to 169 ± 11 beats.min^{-1}, 65-90% HRmax) (ACSM, 1998).

3.3.4 Discussion

This study is the first to examine the HR responses to conventional Taekwondo training activities practiced by experienced practitioners in an ecologically valid training environment. The main findings of the investigation demonstrate that different Taekwondo training activities mediate diverse cardiovascular requirements. In support of the original hypothesis, the cardiovascular intensities of ecologically valid Taekwondo practices were markedly lower than those produced by laboratory-based training simulations, and they may have been insufficient to elicit the cardiovascular adaptations required for competition. Coaches may, therefore, need to reconsider the structure of Taekwondo practices and sessions to ensure that the cardiovascular intensities are sufficient to prepare competitors' for the demands of competition.

The ecologically valid Taekwondo training activities in this study elicited HRs into 65-81% of practitioners HRmax. All of the Taekwondo activities elicited suitable intensities for developing and maintaining cardiovascular fitness in healthy adults (55-90% HRmax) (ACSM, 1998). Considerable disparity was, however, identified between the relative intensities elicited in the current field based study (65-81% HRmax) and previous simulations of Taekwondo practice (80-92% HRmax) (Pieter *et al.*, 1990; Toskovic *et al.*, 2002). This disparity may be caused by differences in the complexity of the technical routines, variation in the participants experience and training status (Bransford & Howley, 1977; Morgan *et al.*, 1995; Jones & Unnithan, 1998), and the ecological validity of the test protocols. Pieter et al. (1990) examined a training simulation in the laboratory, utilising inexperienced participants, and unrealistic work to rest ratios, number of actions and durations of practice. Variation in the work to rest ratios, the number of actions and the duration of practice can significantly alter the mean HR response (Shaw & Deutsch, 1982; Ballor & Volovsek, 1992; Kravitz *et al.*, 2003). Toskovic et al. (2002), on the other hand, evaluated a simulated 'Dynamic Taekwondo' training session. Dynamic Taekwondo actions are performed in a more cyclic manner, which elicit more sustained HR responses (Shaw & Deutsch, 1982; Toskovic *et al.*, 2002). This highlights the importance of adopting an ecological approach to assess of the cardiovascular responses of specific training activities.

Technical practices including elastics, step sparring and technical combinations elicited moderate relative exercise intensities. These cardiovascular intensities suggest that such activities may be better suited to developing functional strength, power and correct technique as opposed to cardio-respiratory adaptations. The practice of technical combinations with pads for additional resistance significantly increased the mean HR responses from moderate to hard relative exercise intensities. This suggests that the use of pads during these technical practices may promote greater cardio-respiratory adaptations. The cardiovascular responses to technical combinations in this study (70% HRmax) were considerably lower than reported by previous research (91% HRmax) (Pieter *et al.*, 1990). As highlighted in the previous section, this cardiovascular incongruity may be a consequence of differences in the complexity of the technical routines, variation in the participants experience and training status, and the ecological validity of the training sessions. As such, the current findings may provide a more accurate representation of the HR responses to technical combinations performed by experience practitioners in conventional training sessions. The accumulated practice duration of these activities during each training session seemed to satisfy the current guidelines for improving and maintain cardiovascular fitness ($\geq$ 20 minutes) (ACSM, 1998), with the exception of one elastics session (11 minutes) and one technical combination session (5 minutes). Although the current ACSM's cardiovascular conditioning guidelines have been formulated from studies that have investigated various exercise modes, it seems logical to apply these guidelines until further evidence is apparent from Taekwondo-specific conditioning studies. Taekwondo-specific evidence is restricted to a single investigation, which demonstrates that forms practice for $\leq$ 10 minutes was insufficient to elicit cardiovascular adaptations (Melhim, 2001).

The practice of forms and the interchangeable practice of basic techniques and forms elicited significantly greater cardiovascular demands than elastics, step sparring, technical combinations and pad work. This suggests that such practices may be particularly suited to developing practitioners' technical aptitude while maximising cardio-respiratory adaptations. Paradoxically, however, previous research has identified negligible changes in Taekwondo practitioners $\dot{V}O_{2max}$ following eight-weeks of forms practice (Melhim, 2001). This is possibly a function of the experimental design. The author included an homogenous sample of adolescent boys, inadequate forms protocol for the experience of the participants and the forms practices failed to satisfy the minimum exercise duration required to improve cardiovascular fitness (ACSM, 1998; Melhim, 2001). The findings of the current study are compatible with the practice intensity of forms in previous Taekwondo research (≈ 80% HRmax) (Pieter *et al.*, 1990). The practice duration of forms, and basic techniques and forms during each session satisfied the current cardiovascular conditioning recommendations, but these were at the lower end of the recommended duration (20-26 minutes).

The practice of sparring drills (81% HRmax) and free sparring (81% HRmax) elicited the greatest demands upon the cardiovascular system. This finding may suggest that these practices are most suitable for developing and maintaining cardio-respiratory fitness for competition. Previous research has, however, reported substantially higher mean HR responses to championship Taekwondo competition (93-100% HRmax) (Chapter 3.1) (Heller *et al.*, 1998). This disparity may be a function of variation in the stress responses to competition and training, differences in the practitioners' fitness status between the investigations or it may reflect the inappropriateness of training to emulate the demands of competition. The potential of the stress response to influence HR during competition has been highlighted in analogous combat sports. In karate, for instance, pre-combat HR was typically 16% higher (14 beats.min^{-1}) in championship competition than in practice combat (Imamura *et al.*, 1996). The presence of pre-competitive state anxiety (somatic and cognitive dimensions) has also been documented in Taekwondo competition (Chapman *et al.*, 1997).

Although sparring drills and free sparring appear to be the most suitable activities to prepare competitors for the cardiovascular demands of Taekwondo competition, only a small proportion of time was devoted to these activities during each session. In addition, the practice duration of free sparring during each session was often below the minimum duration of twenty-minutes required to improve and maintain cardiovascular fitness (ACSM, 1998). As such, the intensity of both these training activities and the duration of free sparring appear to be insufficient to prepare competitors for the cardiovascular demands of Taekwondo competition. If this trend is common across the Taekwondo community, it may partly explain the low to moderate $\dot{V}O_{2max}$ values exhibited by some traditional Taekwondo athletes (44.0 to 53.9 ml.kg^{-1}.min^{-1}) (Thompson & Vinueza, 1991; Heller *et al.*, 1998).

3.3.5. Conclusions and Practical Applications

The main findings of this study demonstrate that different Taekwondo training activities mediate diverse cardiovascular requirements. Practically, this information is valuable to assist coaches in the selection of specific activities in accordance with the training session objectives. Unfortunately, however, the intensities of these conventional training activities and the duration of some activity practices, such as free sparring, may have been insufficient to elicit the cardiovascular adaptations required for competition. These findings suggest that Taekwondo conditioning sessions need to be structured not only in consideration of the technical and tactical needs of the competitors, but also in a manner that enables sufficient cardiovascular conditioning for competition. Sparring-based activities and sessions that replicate the activity pattern of championship combats may elicit suitable cardiovascular intensities for this purpose. The duration and frequency of these activity practices may also need to conform to the current guidelines for improving and maintaining cardiovascular fitness in healthy adults.

CHAPTER 4

DEVELOPMENT OF A TAEKWONDO COMPETITION SIMULATION

4.1 DEVELOPMENT OF AN EXERCISE PROTOCOL THAT SIMULATES THE ACTIVITY PATTERN OF INTERNATIONAL TAEKWONDO COMPETITION

4.1.1 Introduction

The physiological demands of Taekwondo combat have been examined by obtaining physiological measures in championship (Chapter 3.1) (Heller *et al.*, 1998; Matsushigue *et al.*, 2009) and simulated Taekwondo competition (Bouhlel *et al.*, 2006), by studying the activity profiles of Taekwondo competition (Chapter 3.2) (Heller *et al.*, 1998; Matsushigue *et al.*, 2009) and by indirectly assessing the physical capabilities of elite Taekwondo competitors (Pieter, 1991; Thompson & Vinueza, 1991; Heller *et al.*, 1998). While the available data provide important information concerning the energetic demands of Taekwondo combat, this knowledge is restricted to a limited number of time-motion observations and studies in which standard field-based physiological assessments, such as HR and blood lactate, have been evaluated. The evaluation of additional metabolic parameters would advance the understanding of the physiological demands of this combat sport by providing a more comprehensive insight into the energetic requirements of the activity (Kraemer *et al.*, 2001; Degoutte *et al.*, 2003; Barbas *et al.*, 2010).

Collecting physiological measures in an actual championship event would be ecologically favourable to advance knowledge of the energetic demands of Taekwondo combat (Chapter 3.1 & 3.2) (Drust *et al.*, 2007; Chiodo *et al.*, 2009). A range of difficulties have been highlighted by adopting this approach, such as the constraints of carrying out detailed physiological assessments in this setting and the inability to provide appropriate experimental control of the environment (Chapter 2.5) (Drust *et al.*, 2007). In an attempt to circumvent these constraints, a number of researchers have devised exercise protocols that serve to replicate the activity profile and physiological responses of competition in a number of sports (Drust *et al.*, 2000; Nicholas *et al.*, 2000; Davey *et al.*, 2003; Thatcher & Batterham, 2004; Greig *et al.*, 2006; Kingsley *et al.*, 2006; Drust *et al.*, 2007; Hayes *et al.*, 2009; Roberts *et al.*, 2010). This experimental paradigm may permit more detailed examination of the physiological responses to specific intermittent activity patterns and it may provide a controlled model to facilitate the study of interventions (Drust *et al.*, 2000; Thompson *et al.*, 2001; Morris *et al.*, 2003; Sunderland *et al.*, 2008; Roberts *et al.*, 2010).

There have been no attempts to devise an exercise protocol that serves to replicate the activity profile of championship Taekwondo combat. Research in this thesis examining the acute physiological responses (Chapter 3.1) and activity profile (Chapter 3.2) of international Taekwondo competition provide the ergonomic framework required to develop and validate an exercise protocol that represents the demands of Taekwondo combat in a controlled setting. The aims of this study were to 1) develop an exercise protocol that serves to replicate the activity profile of international championship Taekwondo combat, and 2) initially examine the external validity and reliability of the physiological load elicited by the exercise protocol. It was hypothesised that the exercise protocol would provide a close approximation of the activity profiles and the physiological responses elicited in championship competition.

4.1.2 Methods

4.1.2.1 Development of the Taekwondo Exercise Protocol

A Taekwondo course was initially devised to represent the usual fighting ranges that occur during combat (e.g. measured during sparring matches) (Figure 4.1.1). These fighting ranges were classified as short, mid, and long in accordance with conventional terminology (Kim *et al.*, 1999). The participants were required to perform specific combat activity sequences on the 1.7 m course and kick-bag in time with an audio signal (Figure 4.1.1). The audio signal provided the participants with specific activity instructions (Table 4.1.1). The audio instructions were recorded using digital audio editing software (Audacity 1.2.6) and a standard microphone. The pre-recorded audio instructions for each activity were subsequently inserted onto a timeline using the digital editing software. This enabled the researcher to set specific audio cues at an accuracy of 0.026978 s in particular sequences. Once the audio cues for the entire exercise protocol were inserted onto the timeline, the Audacity project file (.aup) was exported to 'WAV' format and copied onto a standard data disc (CD-RW). During the exercise protocol, the audio signals dictated each sequence of Taekwondo actions. All of the participants started the exercise protocol at mid fighting range (Figure 4.1.1).

The activity pattern of the exercise protocol was modelled on the time-motion data obtained from international Taekwondo competition (Chapter 3.2). The framework of the protocol was based upon the mean $\pm$ SD data calculated from three weight categories (e.g. fin, feather and heavy weights). The regular fighting, preparatory, non-preparatory, and stoppage activity phases performed in competition formed the fundamental framework of the protocol (Table 4.1.1). These activity phases were arranged into 36 individual cycles of movement (Figure 4.1.2). The individual cycles of movement were assembled to formulate three two-minute blocks of exercise. A one minute rest interval separated each block of exercise. This configuration represented the three two-minute rounds of international combat (Figure 4.1.2) (WTF, 2010). Each individual cycle of movement required the participants to perform either a single non-preparatory or stoppage activity phase followed by a preparatory and/or fighting activity phase. The only exceptions to this structure were the first and last cycles of each round (Figure 4.1.2). This configuration was selected to recreate the regular activity sequences of

Figure 4.1.1: Taekwondo Exercise Protocol Course

competition. The proportion of time devoted to each of these activity phases within each cycle was based on the mean ± SD data measured in international level competition (Chapter 3.2). Each activity phase within each cycle contained a collection of Taekwondo actions that were arranged into irregular sequences (Figure 4.1.2) (Drust *et al.*, 2000). These irregular activity sequences were selected to mimic the typical activity changes that occur in competition. The frequency and duration of discrete activities included in the protocol were also modelled on the mean ± SD time-motion data measured in championship combat (Chapter 3.2). It was not possible to incorporate all of the different competition activities into the design of the Taekwondo protocol due to practical issues. As such, the protocol only included the most frequently occurring combat activities. Pilot studies also identified that particular actions such as blocking, feinting and receiving impacts from an opponent were difficult to control sufficiently on repeated occasions. As such, these actions were omitted from the protocols framework. Where appropriate, the exclusion of particular activities was supplemented with alternative techniques from each activity phase. The exclusion of the full range of kicking techniques, for instance, was supplemented with a greater quantity of turning kicks to ensure that the total number of kicking techniques was similar between the protocol and competition (Table 4.1.3). A greater quantity of general stoppages was also incorporated into the design of the protocol in an attempt to compensate for the additional stoppages that occur as a result of injuries and penalties during competition (Table 4.1.3).

4.1.2.2 Participants

Eight male Taekwondo black belts (mean ± SD, age 20 ± 2 years, body mass 62.8 ± 9.7 kg, height 1.72 ± 0.08 m, competition experience 7 ± 2 years) took part in this study. The sample included two 3rd Dan grades, three 2nd Dan grades and three 1st Dan grades. The participants were regularly competing in various WTF sanctioned senior level international events (e.g. World and European Championships, and European Taekwondo Union A-class international events) under different weight categories. Participants from Fin -54 kg (n = 1), Fly -58 kg (n = 3), Bantam -62 kg (n = 3) and heavy +84 kg (n = 1) weight divisions were included in this study. The participants were informed of the test procedures and potential risks, and informed consent was attained. The project was granted ethical approval in accordance with local University Ethics Framework.

4.1.2.3 Experimental Design

Prior to completing the experimental trials, the participants were familiarised with the exercise protocol (Currell & Jeukendrup, 2008). All familiarisation and experimental trials were conducted in the British national team's training facility using standard regulation mats. During the familiarisation session, the participants were provided with relevant instructions; they observed a physical demonstration of the protocol and then experienced performing the protocol. To determine the external validity of the exercise protocol, all of the participants performed the protocol with the activity profile and physiological responses then examined against championship competition (e.g. Chapters 3.1 and 3.2) (Nicholas *et al.*, 2000; Davey *et al.*, 2003; Roberts *et al.*, 2010). All of the participants performed the exercise protocol on a second occasion to establish the reliability of the physiological and perceived exertion responses. Each exercise protocol trial was separated by a period of one week and it was performed at the same time of day to control for circadian variation (Drust, Waterhouse, Atkinson, Edwards & Reilly, 2005). To prevent differences in the intensity of the warm-up from influencing the physiological demands during each exercise trial (Bishop, Bonetti & Dawson, 2001; Gray & Nimmo, 2001), the participants were instructed to reproduce the same standardised warm-up. Nutritional intake was recorded via a food diary for 24 hours leading up to the first exercise trial, and the participants were instructed to consume the same diet in preparation for the second exercise trial. This approach was favoured to minimise the confounding influences of differences in energy intake on the physiological responses between the exercise trials (Langfort, Zarzeczny, Pilis, Nazar & Kaciuba-Uscitko, 1997; Mikulski, Ziemba & Nazar, 2010). The ambient temperature and humidity was recorded next to the competition simulation area at 9:00 and 13:00 hrs using a Whirling Psychrometer (G.H. Zeal Ltd, London, UK). The mean ± SD temperature and humidity were 18 $\pm$ 2 ^oC; 17 $\pm$ 1 ^oC and 16 $\pm$ 1 %; 14 $\pm$ 2 % for trials 1 and 2 respectively.

Table 4.1.1: Taekwondo Exercise Protocol Activities

Activity Phase	Time (s)	Audio Signal	Descriptions
Fighting Activity			
Turning Kick	0.8	‘right’ ‘left’ ‘double’	Turning kicks were executed using both right and left segments at mid-section body height. A double kick comprised kicking combinations executed with the back leg (right) followed by front leg (left) in succession. The participants were instructed to execute these movements as forcefully as possible onto the target.
Push	1.2	‘push’	Pushing techniques represented prohibited acts (Chapter 3.2) and required the participants to push against the kick-bag with their hands/chest as forcefully as possible for the allocated time. A researcher of equivalent weight provided equal resistance in the opposite direction.
Preparatory Activity			
Slide	0.8	‘short’ ‘mid’ ‘long’	Sliding actions were executed along the course outlined in figure 4.1.1. Sliding actions were executed as fast as possible between short, mid and long fighting ranges to mimic the intense movements that occur prior to attacking and counter-attacking.
Bounce	0.8-6.5	‘beep’	Bouncing was performed for different time periods. A ‘beep’ signalled the end of ‘walk’ and/or ‘return’ time. The participants’ were instructed to begin bouncing upon hearing this signal and continue until the next instruction. The participants were also instructed to continue bouncing throughout each preparatory activity period (e.g. while not performing slides and steps). The mean duration of each bounce lasted approximately 0.8 s.
Step	1.0	‘step to mid’	On the instruction ‘step to mid’ the participants were required to step from long to mid range (figure 4.1.1). This occurred after the walking period and required, on average, 4 steps to return to mid range.

Table 4.1.1: Continued

Activity Phase	Time (s)	Audio Signal	Descriptions
Non-Preparatory Activity			
Active movement (walk)	4.0	'walk'	Walking represented the active movement occurring during this phase (Chapter 3.2). Walking only took place after the execution of fighting activities. On completion of either kicking or pushing, the signal 'walk' required the participants to walk from the short to long fighting range. The pace of the walking period was dictated by the 'beep' audio signal.
Referee Stoppage			
General (return)	1.6	'return'	To represent the general referee stoppages and a proportion of the stoppages occurring due to injury and knock downs, the participants were instructed to step backwards on the signal 'return'. This movement only occurred after the execution of fighting activities. On the signal 'return' the participants were instructed to return from the short to mid fighting range. The end of this movement was signalled with a 'beep', which required the participants to recommence preparatory activity (e.g. bouncing).

Figure 4.1.2: Structure of the Taekwondo Exercise Protocol

Round 1

Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Cycle 11
Start Bounce (6s) Short (0.8s) Mid (0.8s) Kick R (0.8s)	Walk (4s) Short (0.8s) Mid (0.8s) Kick L (0.8s)	Return (1.6s) Bounce(2.4s) Kick R (0.8s) Kick R (0.8s)	Return (1.6s) Bounce(1.6s) Short (0.8s) Mid (0.8s) Kick L (0.8s) Push (1.2s)	Walk (4s) Step (1s) Bounce (3s) Short (0.8s) Mid (0.8s) Bounce(4.8s) Short (0.8s) Mid (0.8s) Kick L (0.8s)	Walk (4s) Step (1s) Bounce(1.2s) Short (0.8s) Kick R (0.8s) Push (1.2s)	Return (1.6s) Bounce (4s) Kick R (0.8s)	Return (1.6s) Bounce (5s) Short (0.8s) Mid (0.8s) Bounce(4.6s) Long (0.8s) Mid (0.8s) Push (1.2s)	Return (1.6s) Bounce(6.5s) Long (0.8s) Mid (0.8s) Kick L (0.8s)	Walk (4s) Step (1s) Bounce (3s) Short (0.8s) Mid (0.8s) Bounce(3.8s) Short (0.8s)	Return (1.6s) Bounce (4s) Short (0.8s) Mid (0.8s) Bounce (4s) Long (0.8s) Mid (0.8s) Long (0.8s) Mid (0.8s) Bounce(5.6s)

Round 2

Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Cycle 11	Cycle 12
Start Bounce(3.8s) Short (0.8s) Mid (0.8s) Kick R (0.8s) Push (1.2s)	Return (1.6s) Bounce(2.8s) Double (1.6s)	Walk (4s) Step (1s) Long (0.8s) Mid (0.8s) Kick R (0.8s)	Return (1.6s) Double (1.6s)	Walk (4s) Step (1s) Bounce (3s) Short (0.8s) Bounce(3.2s) Kick R (0.8s)	Return (1.6s) Bounce (4s) Kick R (0.8s) Push (1.2s)	Return (1.6s) Bounce(0.8s) Long (0.8s) Mid (0.8s) Kick L (0.8s)	Walk (4s) Step (1s) Bounce (4s) Short (0.8s) Mid (0.8s) Bounce(3.2s) Long (0.8s) Mid (0.8s) Kick L (0.8s) Push (1.2s)	Return (1.6s) Long (0.8s) Mid (0.8s) Push (1.2s)	Walk (4s) Step (1s) Bounce (3s) Short (0.8s) Mid (0.8s) Bounce(2.6s) Short (0.8s) Kick R (0.8s)	Return (1.6s) Bounce(6.4s) Long (0.8s) Mid (0.8s) Push (1.2s)	Walk (4s) Step (1s) Bounce (4s) Long (0.8s) Mid (0.8s) Bounce (5s) Short (0.8s) Mid (0.8s) Bounce(5.2s) Short (0.8s) Mid (0.8s)

Round 3

Cycle 1	Cycle 2	Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Cycle 8	Cycle 9	Cycle 10	Cycle 11	Cycle 12	Cycle 13
Start Bounce(3.8s) Short (0.8s) Mid (0.8s) Kick R (0.8s)	Return (1.6s) Short (0.8s) Mid (0.8s) Double (1.6s)	Return (1.6s) Kick L (0.8s)	Walk (4s) Step (1s) Bounce(3.4s) Short (0.8s) Kick R (0.8s)	Walk (4s) Step (1s) Bounce(2.4s) Short (0.8s) Mid (0.8s) Kick L (0.8s)	Return (1.6s) Bounce(2.4s) Kick R (0.8s) Kick R (0.8s)	Return (1.6s) Kick R (0.8s)	Walk (4s) Step (1s) Bounce (4s) Long (0.8s) Mid (0.8s) Bounce(3.4s) Kick L (0.8s) Push (1.2s)	Walk (4s) Step (1s) Bounce (4s) Short (0.8s) Mid (0.8s) Bounce(4s) Short (0.8s) Mid (0.8s) Double (1.6s)	Return (1.6s) Bounce(3.8s) Push (1.2s)	Return (1.6s) Kick R (0.8s) Double (1.6s)	Walk (4s) Step (1s) Bounce(4.8s) Short (0.8s) Mid (0.8s) Push (1.2s)	Walk (4s) Step (1s) Bounce(3s) Short (0.8s) Mid (0.8s) Bounce (3s) Long (0.8s) Mid (0.8s) Bounce(3.2s) Short (0.8s) Mid (0.8s) Bounce (2s)

4.1.2.4 Validation of the Activity Profiles

The activity profile of the exercise protocol was examined against the time-motion data obtained from international Taekwondo competition (Chapter 3.2). This approach made it possible to determine the effectiveness of the protocol as an analogue of the combat activity. The overall activity profile in the exercise protocol closely replicated the combat activity performed in international level Taekwondo competition (Table 4.1.2). Both the frequency and duration of activities performed in the protocol compare favourably with the mean $\pm$ SD values reported in international Taekwondo competition (Tables 4.1.2 and 4.1.3). The changes in activity across the rounds of the protocol were similar in magnitude to those performed across the rounds of championship combat.

4.1.2.5 Physiological Assessments

Heart rate was recorded at 5 s intervals throughout the exercise protocol to assess the relative cardiovascular strain of each round (See Chapter 3.1.2.2 for further details of this procedure). Whole blood lactate concentrations were measured before and directly after each round to determine the energy production from anaerobic glycolysis (See Chapter 3.1.2.2). Borg's 6-20 scale was used as an additional methodology to describe and monitor the intensity of each round (See Chapter 3.1.2.2). This approached made it possible to compare the physiological and perceived exertion responses between the protocol and championship competition (Chapter 3.1).

4.1.2.6 Statistical Analysis

The mean $\pm$ SD data were calculated for each dependent variable. All of the data were assessed for normality using Shapiro-Wilks test prior to performing inferential statistical analysis. A repeated measures ANOVA was performed on each of the dependent variables (HR, blood lactate and RPE) to identify differences in these parameters across the rounds of the protocol. Post-hoc analysis included pair-wise comparisons using Bonferroni interval adjustment. The mean $\pm$ SD HR, blood lactate and RPE data obtained from the exercise protocol were compared against the corresponding championship competition data (e.g. the descriptive statistics obtained in Chapter 3.1) to determine the validity of the physiological and perceived exertion responses. A two-way (round x trial) ANOVA was performed on the data to determine differences in the physiological and perceived exertion responses between trials 1 and 2 of the exercise protocol. The CV and Bland and Altmans Limits of Agreement (LOA) were calculated for each of the dependent variables to examine the agreement of the physiological and perceived exertion responses between the repeated exercise protocol trials. Significance was set at $P < 0.05$.

4.1.3 Results

4.1.3.1 Evaluation and Validation of the Physiological and Perceived Exertion Responses

The physiological and perceived exertion responses to the exercise protocol and international level Taekwondo competition are presented in Table 4.1.4. During the exercise protocol mean HR ($P < 0.001$), %HRmax ($P < 0.001$) and blood lactate ($P < 0.001$) increased significantly between the pre-combat period and round 1, and these parameters remained significantly higher throughout rounds 2 and 3 (Table 4.1.4). Significant increases in HR ($P = 0.02$), %HRmax ($P = 0.04$) and RPE ($P < 0.001$) were also evident between rounds 1 and 3 of the exercise protocol. In contrast, blood lactate concentrations were similar between rounds 1 and 3 ($P = 0.11$). No differences in HR ($P = 0.14$; $P = 0.80$), %HRmax ($P = 0.25$; $P = 0.78$), blood lactate ($P = 0.67$; $P = 0.63$) and RPE ($P = 0.11$; $P = 0.08$) were identified between rounds 1 and 2, and rounds 2 and 3, respectively. The significant increases in HR, %HRmax and RPE across the rounds of the exercise protocol demonstrated a similar trend to those in international competition (Table 4.1.4). The overall HR and blood lactate responses in the exercise protocol were, however, appreciably lower than reported in international Taekwondo competition (Table 4.1.4).

4.1.3.2 Reliability of the Physiological and Perceived Exertion Responses

No differences in HR ($P = 0.87$), blood lactate ($P = 0.63$) and RPE ($P = 0.98$) were identified between the two exercise protocol trials (Table 4.1.5). Furthermore, no significant interaction between the trials and rounds were identified for HR ($P = 0.94$), blood lactate ($P = 0.51$) and RPE ($P = 0.97$). The CVs for each dependent variable are presented in Table 4.1.5. The 95% LOA for HR, blood lactate and RPE were -2.6 to 3.2 beats.min^{-1}, -0.5 to 0.3 mmol.l^{-1} and -0.6 to 1.4 units respectively. The associated Bland-Altman plots for these variables are presented in figure 4.1.3.

Table 4.1.2: The frequency and duration of activities during the exercise protocol and international level Taekwondo competition (mean ± SD).

Activity Phase	Round 1		Round 2		Round 3		Mean	
	Competition	Protocol	Competition	Protocol	Competition	Protocol	Competition	Protocol
Fighting Activity (s)	1.7 ± 0.4	1.3	1.7 ± 0.4	1.3	1.7 ± 0.5	1.3	1.7 ± 0.4	1.3
Preparatory Activity (s)	9.7 ± 5.7	7.6	7.0 ± 1.7	6.8	5.7 ± 2.0	6.8	6.4 ± 2.1	7.0
Non Preparatory Activity (s)	3.3 ± 1.2	4.0	2.9 ± 0.8	4.0	2.8 ± 0.9	4.0	3.0 ± 0.6	4.0
Referee Stoppage (s)	2.0 ± 0.8	1.6	3.0 ± 0.9	1.6	2.9 ± 0.9	1.6	2.8 ± 0.9	1.6
Fighting:Non-fighting Ratio (1:x)	7.8 ± 4.2	7.3	5.5 ± 1.2	5.5	4.9 ± 2.1	5.3	6.3 ± 2.0	6.0
Number of Exchanges	8 ± 3	9	9 ± 2	11	11 ± 2	12	28 ± 6[#]	32[#]
Number of Kicks	8 ± 4	9	10 ± 3	11	13 ± 4	15	31 ± 7[#]	35[#]

Notes: Competition combat data is obtained from Chapter 3.2
[#] Values represent the sum of each round

Table 4.1.3: Total frequency of activities during the exercise protocol and international level Taekwondo competition (Mean ± SD).

Activity Phase	**Competition**	**Protocol**
Fighting Activity[#]		
Turning Kick	29 ± 5	35
Back Kick	2 ± 1	-
Front Kick	2 ± 2	-
Side Kick	1 ± 0	-
Push Kick	1 ± 1	-
Axe Kick	1 ± 1	-
Hook Kick	1 ± 1	-
Punch	2 ± 1	-
Block	5 ± 5	-
Prohibited Act (Push)	13 ± 7	11
Preparatory Activity		
Stand	13 ± 9	-
Bounce	200 ± 91	160
Slide	81 ± 35	70
Step	113 ± 64	56
Turn	6 ± 5	-
Feint	56 ± 32	-
Non Preparatory Activity		
Stand	1 ± 1	-
Move	19 ± 9	15
Referee Stoppage		
General	8 ± 5	18*
Injury	5 ± 3	
Penalty	6 ± 3	

Notes: [#] Crescent kicks and Spinning hook kicks were not executed during competition evaluations; * See table 4.1.1 and chapter 4.1.2.3 for further details of the rationale for this quantity.

Table 4.1.4: Physiological and perceived exertion responses to the exercise protocol and international competition (mean ± SD)

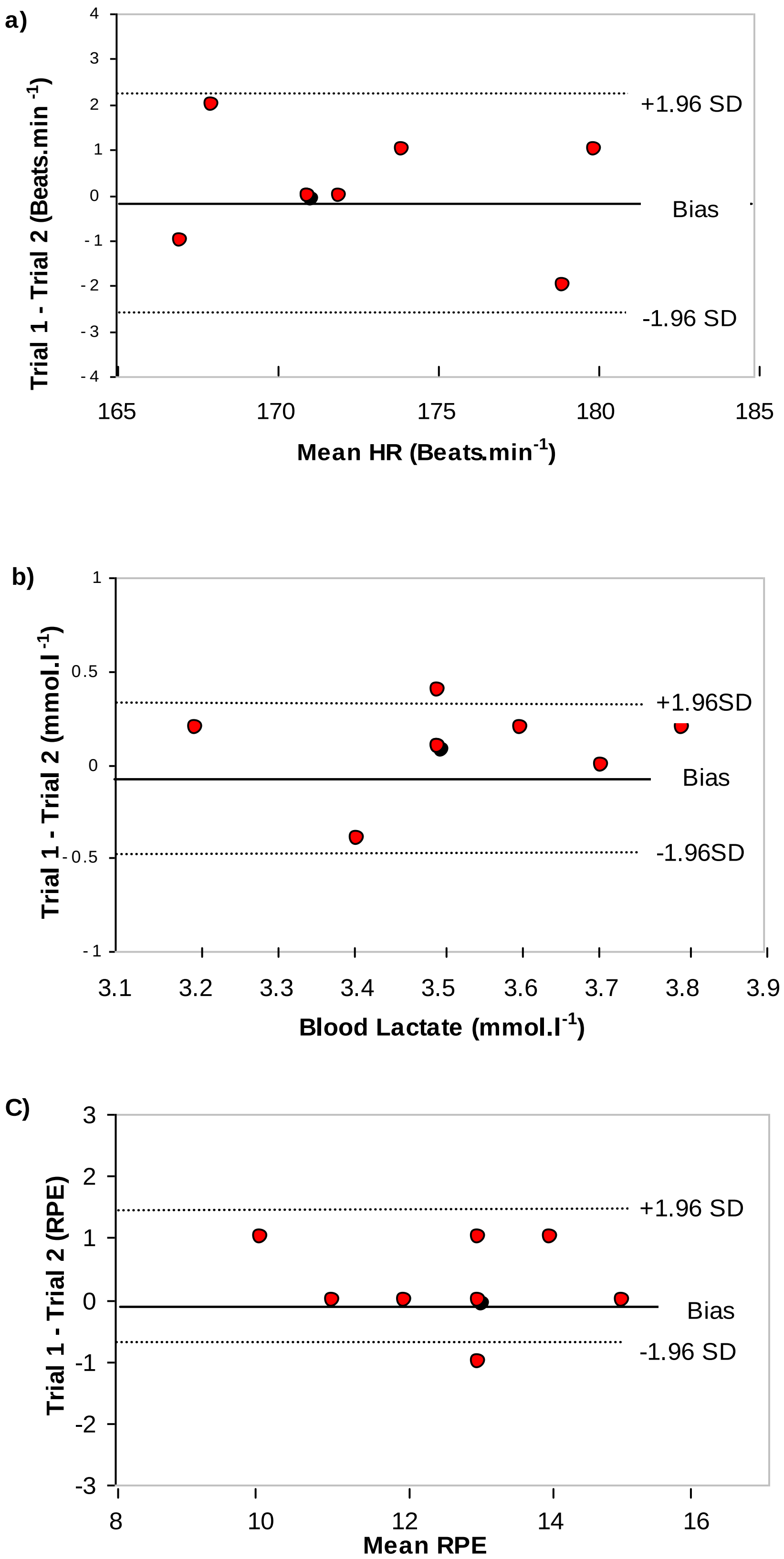
	HR ($beats.min^{-1}$)		% HRmax		Blood Lactate ($mmol.l^{-1}$)		RPE (6-20 scale)	
	Competition	Protocol	Competition	Protocol	Competition	Protocol	Competition	Protocol
Pre-Combat	123 ± 6*	114 ± 7*	62 ± 3*	57 ± 4*	2.7 ± 0.6*	2.7 ± 0.4*	-	-
Round 1	175 ± 15	168 ± 5	89 ± 8	84 ± 3	7.5 ± 1.6	3.4 ± 0.3	11 ± 2	11 ± 2
Round 2	183 ± 12	174 ± 5	93 ± 6	87 ± 2	10.4 ± 2.4^	3.5 ± 0.3	13 ± 2	13 ± 1
Round 3	187 ± 8^	177 ± 5^	96 ± 5^	88 ± 3^	11.9 ± 2.1^	3.7 ± 0.2	14 ± 2^	15 ± 2^
Mean	182 ± 6	173 ± 5	93 ± 3	86 ± 3	9.9 ± 2.3	3.5 ± 0.2	13 ± 2	13 ± 1

Note: competition data obtained from Chapter 3.1
* Denotes pre-combat values are significantly lower than reported in rounds 1, 2 and 3 in the same condition ($P < 0.01$). ^ Denotes values are significantly different than round 1 in the same condition ($P < 0.05$).

Table 4.1.5: Physiological and perceived exertion responses during trials 1 and 2 of the exercise protocol (mean $\pm$ SD)

	HR (beats.min^{-1})			Blood Lactate (mmol.l^{-1})			RPE (6-20 scale)		
	Trial 1	Trial 2	CV (%)	Trial 1	Trial 2	CV (%)	Trial 1	Trial 2	CV (%)
Pre-Combat	114 $\pm$ 7	112 $\pm$ 6	-	2.7 $\pm$ 0.4	2.5 $\pm$ 0.5	-	-	-	-
Round 1	168 $\pm$ 5	166 $\pm$ 5	0.6	3.4 $\pm$ 0.3	3.6 $\pm$ 0.4	7.9	11 $\pm$ 2	11 $\pm$ 1	4.9
Round 2	174 $\pm$ 5	175 $\pm$ 4	0.4	3.5 $\pm$ 0.3	3.7 $\pm$ 0.4	7.1	13 $\pm$ 1	13 $\pm$ 2	3.6
Round 3	177 $\pm$ 5	178 $\pm$ 5	0.5	3.7 $\pm$ 0.2	3.7 $\pm$ 0.4	5.6	15 $\pm$ 2	15 $\pm$ 2	4.1
Mean	173 $\pm$ 5	173 $\pm$ 5	0.6	3.5 $\pm$ 0.2	3.7 $\pm$ 0.3	7.0	13 $\pm$ 1	13 $\pm$ 1	4.0

Figure 4.1.3: Bland-Altman plots for (a) Heart rate; (b) Blood lactate; and (c) RPE calculated from two trials of the Taekwondo protocol



4.1.4 Discussion

The aim of this investigation was to devise an exercise protocol that serves to replicate the activity profile of international Taekwondo combat. The exercise protocol presented in this study provided a close approximation of the activity profile, the changes in activity and the most frequent activities performed in international Taekwondo combat under controlled conditions. In contrast to the hypothesis, the HR and blood lactate responses to the exercise protocol were markedly lower than those measured in championship Taekwondo competition. This finding may restrict the application of the exercise protocol in the study of the physiological demands of Taekwondo combat.

The activity pattern of the exercise protocol was modelled on the time-motion data obtained from international Taekwondo competition (Chapter 3.2). The mean frequency and duration of fighting, preparatory, non-preparatory and referee stoppage activities were similar between the exercise protocol and international competition (Tables 4.1.2 & 4.1.3). The exercise protocol also provided an accurate representation of the increased activity levels performed across the rounds of international combat. In agreement with the available competition data (Chapter 3.2), the increased activity levels in the exercise protocol reflected reductions in the preparatory activity and fighting to non-fighting ratios, and an increase in the number of exchanges and kicks across the rounds. Such similarities highlight the relevance of the exercise protocol as a model of the combat activity.

The mean HR, %HRmax and RPE responses increased significantly across the rounds of the exercise protocol. The trend for the increased cardiovascular and RPE demands between round 1 and 3 were similar between the exercise protocol and international Taekwondo competition (Table 4.1.4). The physiological responses to Taekwondo-specific exercise (Bouhlel *et al.*, 2006) and other combat sport activities (Iide *et al.*, 2008; Baudry & Roux, 2009) are sensitive to changes in both the work and rest intervals. As such, it is plausible that the elevated cardiovascular and perceived exertion responses across the rounds of the exercise protocol were mediated by the increased activity levels. This highlights the appropriateness of the exercise protocol as a model of the increased activity, and the elevated cardiovascular and perceptual strain in combat. Blood lactate increased significantly between the pre-combat sampling period and round 1, and it remained elevated throughout the duration of the exercise protocol. This blood lactate response concurs with international combat.

While the trend for increased cardiovascular demands across the rounds was similar between the exercise protocol and international competition (Table 4.1.4), a disparity in the overall cardiovascular strain was evident between these combat settings. The mean HR elicited in the exercise protocol was 9 beats.min^{-1} (7% HRmax) lower than measured in international competition

(Chapter 3.1). This finding may suggest that international Taekwondo combats elicit greater cardiovascular requirements than the exercise protocol. There was a clear dissociation between the blood lactate responses in the exercise protocol and international competition. The mean post-combat blood lactate concentration was 6.4 $mmol.l^{-1}$ lower in the exercise protocol than in international competition. In contrast to international competition (Chapter 3.1), blood lactate demonstrated little fluctuation during the rounds of the exercise protocol. This response was evident even though the activity levels increased in both combat settings. The HR and blood lactate responses to the exercise protocol were also lower than those elicited in national level Taekwondo competition (Heller *et al.*, 1998; Matsushigue *et al.*, 2009) and simulated Taekwondo competition (Bouhlel *et al.*, 2006), yet they correspond with the values reported in a recent simulation of Taekwondo combat (Butios & Tasika, 2007) (Chapter 3.3). Paradoxically, the overall RPE responses elicited in the exercise protocol and the trend across the rounds corroborate those measured in international level Taekwondo competition (Chapter 3.1 & Table 4.1.4). This demonstrates that the RPE responses to these combat settings were similar regardless of the variation in the physiological load.

The mechanisms that govern the physiological incongruity between the simulated and championship combats are difficult to quantify effectively from the available information. This may be a function of a number of factors including variation in the competitors' fitness status between the investigations, the exclusion of specific activities from the exercise protocol and/or variation in the 'stress responses' to these combat settings (Pierce *et al.*, 1976; Hoch *et al.*, 1988; Baron *et al.*, 1992; Ferrauti *et al.*, 2001; Haneishi *et al.*, 2007). An adequate appraisal of the competitors' physical capabilities was not undertaken in either of these investigations. This oversight makes it difficult to determine whether differences in the competitors' fitness status may have contributed to the divergent physiological responses to these simulated and championship combat settings. The current study and previous evaluations of international level competition (Chapter 3.1) did, however, examine competitors of similar technical ability and competition experience, and both groups were regularly competing in WTF international level events. Theoretically, this would mitigate the influence of differences in fitness status on the physiological responses in these settings.

While the exercise protocol provides a reasonable approximation of the combat activity, a number of limitations in the activity profiles between the exercise protocol and international competition can observed. This is similar to a number of simulation protocols available in the literature (Drust *et al.*, 2000; Nicholas *et al.*, 2000; Davey *et al.*, 2003). These limitations include a lower overall frequency of preparatory activities in the protocol, and the exclusion of particular activities such as feints, blocks, specific kicking techniques and the impacts received from an opponent. These activities were omitted from the design of the exercise protocol because of practical issues (see Chapter 4.1.2.3 for specific details). The exclusion of particular activities from the exercise protocol, including the high incidence of impacts typically received from an opponent, could attenuate the energetic requirements in comparison to championship combat. It is possible, therefore, that these activity omissions could contribute to the reduced physiological responses observed in the exercise protocol. In contrast to this presumption, recent studies examining full-contact forms of simulated Taekwondo combat (e.g. that include feints, blocks and the impacts typically received from an opponent), also demonstrate a proclivity for reduced physiological loads in comparison to international competition (Butios & Tasika, 2007) (Chapter 3.3). This evidence may, therefore, exonerate differences in the physical workload (e.g. activity omissions) and fitness status as key factors mediating the incongruent physiological load between these settings.

There is compelling evidence to implicate dissonant stress hormonal responses as a primary mediator of the incongruent physiological responses between these simulated and championship combat settings. In elite fencers, for instance, championship combats have evoked higher cortisol and catecholamine concentrations (adrenaline) than equivalent practice combats (Hoch *et al.*, 1988). The higher hormonal responses in the championship fencing combats were also accompanied by greater HR responses, and plasma lactate and glucose concentrations. The authors advocate that the greater adrenaline concentrations, as a consequence of higher emotional strain, may have elevated anaerobic muscular glycolysis and glycogenolysis in this setting (Hoch *et al.*, 1988). This notion is quite conceivable (Gerra *et al.*, 2001; Watt *et al.*, 2001). Interestingly, significantly higher plasma cortisol concentrations have been identified in the moments before (1 to 4 hours) and after championship Taekwondo combats than during the equivalent periods of simulated combat (Obminski, 2008). These data appear to affirm greater stress hormonal responses in championship Taekwondo combats (Ferrauti *et al.*, 2001; Gerra *et al.*, 2001). It is possible, therefore, that the incongruent physiological responses identified between these simulated and championship Taekwondo combats may be mediated by the stress responses to fighting in championship events. As the precise mechanistic basis for this response remains obscure, this warrants further research attention.

The mechanisms responsible for the analogous RPE responses in the exercise protocol and competition, despite eliciting divergent physiological loads, are again difficult to quantify from the current study design. This could be a function of variation in the participants direction of attentional focus between the exercise protocol and competition (Johnson & Siegel, 1992; Stanley *et al.*, 2007). In support of this notion, a clear dissociation between competitors' physiological strain and perception of effort has recently been identified in international Taekwondo competition (Chapter 3.1). It was hypothesised that international competition induced high external attentional focus (e.g.

focus upon tactical decision making and emotional strain), which diverted attention away from internal sensory cues (e.g. physiological strain), resulting in a reduced effort sense for a given physiological load (Chapter 3.1). It is possible, therefore, that the exercise protocol and competition present different attentional sensory cues, ultimately resulting in similar RPE responses. Further research is required to substantiate this hypothesis.

4.1.5 Conclusions and Implications

The aim of the current study was to devise an exercise protocol that serves to replicate the activity profile of international Taekwondo combat. This would permit more detailed study of the physiological responses to Taekwondo-specific intermittent exercise. It would also provide a controlled model to facilitate the study of interventions. The exercise protocol presented in this study provided a close approximation of the activity profile, the changes in activity and the most frequent activities performed in international Taekwondo competition under controlled conditions. The perceived exertion responses to the exercise protocol were similar to those measured in international level competition, yet the physiological load was markedly lower. This finding may restrict the application of the exercise protocol in the study of the physiological demands of Taekwondo combat. Further research is necessary to determine whether the incongruent physiological responses between the exercise protocol and international Taekwondo competition are indeed a function of divergent stress hormonal responses or a consequence of other factors. This information may have profound implications for the understanding of the physiological demands of this combat sport.

4.2 PHYSIOLOGICAL AND HORMONAL RESPONSES TO PERFORMING SIMULATED AND CHAMPIONSHIP TAEKWONDO COMBATS

4.2.1 Introduction

Recent efforts to advance knowledge of the energetic requirements of Taekwondo combat have identified marked differences in metabolic function between combats that are contested in simulated and championship settings (Chapter 4.1). Simulated forms of Taekwondo combat have tended to evoke reduced cardiovascular strain and blood lactate concentrations than equivalent championship combats (Chapters 3.3 & 4.1) (Butios & Tasika, 2007). Interestingly, these reduced energetic requirements have been documented even though both combat settings exhibit comparable activity profiles (Chapter 4.1). As the mechanistic basis for this response has not been elucidated, there is merit in exploring this phenomenon. This information may have significant implications for the understanding of the physiological demands of this combat sport.

A number of prospective theories have been formulated to explicate the disparate physiological responses to these simulated and championship forms of Taekwondo combat. These include differences in the competitors' fitness status between the investigations, the exclusion of particular activities from the simulated combats and variation in the stress hormonal responses to the simulated and championship combats (Chapter 4.1) (Butios & Tasika, 2007). While several causal factors have been identified, there is compelling evidence to implicate dissonant stress hormonal responses as a primary mediator of the incongruent physiological responses in these combat settings (Hoch *et al.*, 1988; Erickson *et al.*, 2003; Obminski, 2008; Chiodo *et al.*, 2009). The aim of this study was to compare the physiological and stress hormonal responses to performing Taekwondo combats in simulated and championship settings. It was hypothesised that Taekwondo simulations would not recreate the physiological responses of championship combats as a consequence of the increased stress responses in competition.

4.2.2 Methods

4.2.2.1 Participants

Ten male Taekwondo black belts (mean $\pm$ SD, age 18 $\pm$ 1 years, body mass 64.5 $\pm$ 11 kg, height 1.77 $\pm$ 0.08 m, competition experience 6 $\pm$ 1 years) took part in this study. The sample comprised elite international level competitors from the British national team and British technical centres that had obtained significant results (e.g. medals) during international events. The participants were regularly competing in various WTF sanctioned international level events (e.g. Olympic Games, European Championships and European Taekwondo Union A-class international events), under different weight categories. More specifically, the sample included competitors from Fin -54 kg (n = 1), Fly -58 kg (n = 4), Bantam -63 kg (n = 4) and Heavy +84 kg (n = 1) weight divisions. The participants were informed of the test procedures and potential risks, and written informed consent was obtained. The study was approved by an Institutional Research Ethics Committee.

4.2.2.2 Experimental Design

All of the participants took part in an international Taekwondo championship event and an exercise protocol (simulated combat) that served to replicate the activity profile of international Taekwondo combat in a controlled setting (Chapter 4.1). The championship and simulated combat trials were separated by a period of two weeks. This approach was a compromise between providing the participants with suitable recovery from the demands of the championship event and minimising the potential influence of alterations in fitness status on the physiological responses (Zouhal *et al.*, 2001; Zouhal *et al.*, 2008). The participants were also instructed to maintain similar training loads in the period leading up to each combat. This was an attempt to further mitigate any alterations in the participants' fitness status during the course of the investigation. The participants' physiological and hormonal responses were examined during the first combat of the international championship event and during the simulated combat. The first combat of the championship event was selected to prevent the demands of the previous championship combats from confounding comparisons of the simulated and championship combat demands (Kraemer *et al.*, 2001). The participants performed their first combat at different times during the championship event. As such, the simulated combat times were structured to coincide with the championship combat times in an attempt to control for circadian rhythm influences (Drust *et al.*, 2005). The participants were instructed to complete a basic food diary for the seven days leading up to the championship event and replicate these nutritional practices as closely as possible in preparation for the simulated combat trial. A seven-day diary was selected to capture the competitors' 'rapid' weight making practices leading up to the event (Tsai et al. 2010). This approach was adopted to minimise the influence of differences in energy intake and weight reduction on the physiological and hormonal responses in these combat settings (Langfort *et al.*, 1997; Tsai, Chou, Chang & Fang, 2009; Mikulski *et al.*, 2010; Tsai *et al.*, 2010). No significant difference (P = .53) in the participants mean body mass (kg) was identified during the weight-in (day before) between the championship and simulated combats.

4.2.2.3 Championship Procedures

All of the participants competed in a WTF sanctioned senior level international competition event (British International Championships, Manchester, 2008). The two-day event was staged inside a sports arena and the combats were contested on standard regulation mats. Specific weight divisions competed on separate days. For each competitor all qualifying, semi-final and final phase matches were contested between the hours of 9:00 and 20:00 during the same day. Each combat comprised three rounds of two-minutes with one-minute recovery between each round. The data inclusion criteria were the successful attainment of HR, RPE and venous blood samples during the first combat, and completion of the full three rounds of combat. In total, data from ten individual combats were successfully recorded using these inclusion criteria. The ambient temperature and humidity was recorded at the competition area at 9:00, 13:00 and 18:00 hours on both days using a Whirling Psychrometer (G.H. Zeal Ltd, London, UK). The mean $\pm$ SD temperature and humidity were 21 $\pm$ 2 and 22 $\pm$ 3 ^{o}C; 24 $\pm$ 3 and 26 $\pm$ 3 % for days 1 and 2, respectively.

4.2.2.4 Simulation Procedures

The participants also performed an exercise protocol (simulated combat) that served to replicate the activity profile of international competition in a controlled setting. Information pertaining to the structure, reliability and validity of the simulated Taekwondo combat has been presented in previous sections of the thesis (See Chapter 4.1). Prior to performing the simulated combats, the participants were instructed to replicate the same standardised warm up as undertaken in the period leading up to their first combat in the British International Championships. This approach ensured that different warm up intensities did not confound comparisons of the demands of these simulated and championship combat settings (Bishop *et al.*, 2001; Gray & Nimmo, 2001). No significant difference (P = 0.39) in the mean HR's were identified between the championship (146 $\pm$ 11 beats.min^{-1}) and simulated (144 $\pm$ 10 beats.min^{-1}) combat warm-up periods. The ambient temperature and humidity was recorded in the training facility at 9:00, 13:00 and 18:00 hours during both of the simulated combat testing days using a Whirling Psychrometer (G.H. Zeal Ltd, London, UK). The mean $\pm$ SD temperature and humidity were 18 $\pm$ 2 and 17 $\pm$ 1 ^{o}C; 23 $\pm$ 1 and 24 $\pm$ 4 % for days 1 and 2, respectively.

4.2.2.5 Physiological, Hormonal and RPE Procedures

Heart rate was recorded at 5 s intervals during both the simulated and championship combat conditions to assess the relative cardiovascular strain of these settings (See Chapter 3.1.2.2 for further details of this procedure). The only difference in the HR analytical techniques between these settings (e.g. Chapter 3.1 vs. Chapter 4.2) was the method used to determine HRmax. The competitors HRmax was calculated as the highest value obtained during the championship combat as opposed to using the standard equation 220 – age (Chapter 3.1.2.2). Ratings of perceived exertion (Borg's 6-20 scale) were also collected and used as an additional methodology to describe and monitor the intensity of the simulated and championship combats (Chapter 3.1.2.2).

Venous blood samples were collected both before and after the championship and simulated combats to determine the plasma concentrations of lactate, glucose, glycerol, non-esterified free fatty acids (NEFA), adrenaline and noradrenaline. As a consequence of the high ecological validity of the championship environment, it was not possible to control the exact venous blood sampling times. As such, blood sampling took place at various times in the pre- and post-combat periods. The mean $\pm$ SD pre- and post-combat blood sampling times in the championship event were 9 $\pm$ 4 and 4 $\pm$ 1 minutes respectively. These exact sampling times were replicated in the simulated combat trial for each competitor to prevent variation in the sampling periods from confounding comparisons of the data (Richter *et al.*, 1996). Blood samples were collected via venipuncture from an antecubital arm vein using a butterfly blood collection infusion set (21G x ¾" x 7" tubing; BD Vacutainer Blood Collection Set, BD Diagnostics, Pre-analytical Systems). All of the participants were seated in an upright position during blood draws. Whole blood was collected into di-potassium ethylenediaminetetraacetic acid (K_2EDTA) (6 ml) and Lithium Heparin (6 ml) collection tubes (BD Vacutainer Blood Collection Tubes, BD Diagnostics, Pre-analytical Systems). To prevent contamination from multiple draws, the vacutainer system order of draw was kept constant and comprised Lithium Heparin and K_2EDTA, respectively. Once each vacutainer was filled, the tube was inverted gently according to the manufacturer's recommendations. When possible, the filled K_2EDTA and Lithium Heparin collection tubes were immediately centrifuged at 3000 RPM for 15 minutes. The plasma was subsequently separated and stored in micro collection containers at –78^{o}C until analysis. When immediate centrifuge of the filled K_2EDTA and Lithium Heparin collection tubes was not possible, the tubes were placed in a slurry of crushed ice and water (temperature range: 2-8 ^{o}C) and subsequently centrifuged within 30 minutes of collection.

4.2.2.6 Biochemical Analysis

Plasma lactate, glucose, glycerol and NEFA were analysed using a fully automated random access clinical analyser (RX Daytona, Randox Laboratories Ltd, UK). Lactate was analysed via the enzymatic method, glucose via the glucose oxidase phenol 4-aminoantipyrine peroxidise method (GOD-PAP), NEFA using the colorimetric method and glycerol using the glycerol-3-phosphate oxidase phenol 4-Aminoantipyrine peroxidase (GPO-PAP, Randox Laboratories Ltd, UK) method. Solid phase enzyme-linked immunosorbent assay (ELISA) was used for the quantitative determination of adrenaline and noradrenaline using the manual procedure (CatCombi ELISA, IBL

International, Hamburg, Germany). All of the samples were analysed in duplicate and the intra-assay CV's for lactate, glucose, glycerol and NEFA were < 2 %, and for catecholamines ≤ 6 %.

4.2.2.7 Statistical Analysis

The mean ± SD data were calculated for each dependent variable. All of the data were assessed for normality using Shapiro-Wilks test prior to performing inferential statistical analysis. A two-way (condition x time) repeated measures ANOVA was performed upon the dependent variables to indentify differences in these parameters between the experimental conditions and sampling periods. Where appropriate, multiple comparisons using Bonferroni interval adjustment were employed to determine which particular levels of a factor were significantly different from each other (Atkinson, 2002). Paired t-tests were performed on the mean warm-up HR's and the participants body mass between the combats. Statistical significance was set at $P < 0.05$.

4.2.3 Results

4.2.3.1 Heart rate and rating of perceived exertion

The mean HR, %HRmax and RPE data for the simulated and championship combats are presented in Table 4.2.1. Significant main effects for time were observed for HR ($P < 0.001$), % HRmax ($P < 0.001$) and RPE ($P = 0.001$), with these variables increasing across the rounds (Table 4.2.1). Significant main effects for condition were evident for HR ($P < 0.001$) and % HRmax ($P < 0.001$), with higher values elicited in the championship combats (Table 4.2.1). Interaction effects between condition and time were identified for both HR ($P = 0.029$) and %HR ($P = 0.014$). This interaction represented differences in the magnitude of the increase in these variables between round 1 and 2 in the simulated and championship combats (Table 4.2.1). There was no significant main effect for condition ($P = 0.217$) or evidence of an interaction ($P = 0.646$) for RPE.

4.2.3.2 Plasma Metabolites and Hormones

The mean plasma metabolite and hormone data for the simulated and championship combats are presented in Table 4.2.2. Significant main effects for time were observed for lactate ($P < 0.001$), glucose ($P < 0.001$), glycerol ($P < 0.001$), adrenaline ($P = 0.002$) and noradrenaline ($P = 0.001$). Significant main effects for condition were also identified for lactate ($P < 0.001$), glucose ($P < 0.001$), glycerol ($P = 0.022$) adrenaline ($P = 0.004$) and noradrenaline ($P = 0.002$), with higher concentrations evident in the championship combats (Table 4.2.2). Interaction effects between condition and time were identified for lactate ($P < 0.001$), glucose ($P < 0.001$), glycerol ($P = 0.001$)

adrenaline (P = 0.007) and noradrenaline (P = 0.005). The interactions suggest that the increase in these plasma metabolites and hormones between the pre and post sampling periods were greater in magnitude in the championship combats (Table 4.2.2). No significant main effects were observed for time (P = 0.718) and condition (P = 0.812), or interaction (P = 0.757) for plasma NEFA.

Table 4.2.1: Heart rate and perceived exertion responses for the championship and simulated combats (mean ± SD)

	HR (beats.min^{-1})		% HRmax		RPE (6-20 scale)	
	Championship	Simulation	Championship	Simulation	Championship	Simulation
Pre-Combat	136 ± 13$^{\wedge}$	116 ± 10*$^{\wedge}$	69 ± 6$^{\wedge}$	59 ± 6*$^{\wedge}$	-	-
Round 1	185 ± 7	166 ± 3*	94 ± 2	85 ± 4*	11 ± 2	11 ± 2
Round 2	189 ± 8†	174 ± 4*†	96 ± 1†	89 ± 4*†	12 ± 2†	12 ± 2†
Round 3	190 ± 9†	176 ± 5*†	97 ± 2†	90 ± 3*†	14 ± 3†‡	13 ± 3†‡
Mean	188 ± 8	172 ± 4	96 ± 1	88 ± 4	12 ± 2	12 ± 2

* Denotes significantly lower than the corresponding championship data; $P < 0.05$.
^ Denotes significantly lower than rounds 1, 2, and 3 in the same condition; $P < 0.05$.
† Denotes a significant increase in comparison with round 1 in the same condition; $P < 0.05$.
‡ Denotes a significant increase in comparison with round 2 in the same condition; $P < 0.05$.

Table 4.2.2: Plasma metabolites and hormones for the championship and simulated combats (mean ± SD)

	Championship		Simulation	
	Pre	Post	Pre	Post
Lactate ($mmol.L^{-1}$)	$2.6 \pm 0.9^{*}$	$12.2 \pm 4.6^{*\wedge}$	1.2 ± 0.7	$3.6 \pm 2.7^{\wedge}$
Glucose ($mmol.L^{-1}$)	$6.7 \pm 0.9^{*}$	$10.3 \pm 1.1^{*\wedge}$	5.6 ± 1.2	5.9 ± 0.8
Glycerol ($\mu mol.L^{-1}$)	73.0 ± 28.4	$143.4 \pm 49.4^{*\wedge}$	58.9 ± 26.9	$77.7 \pm 21.3^{\wedge}$
NEFA ($mmol.L^{-1}$)	0.67 ± 0.26	0.64 ± 0.29	0.63 ± 0.23	0.63 ± 0.25
Adrenaline ($nmol.L^{-1}$)	0.5 ± 0.3	$2.7 \pm 1.7^{*\wedge}$	0.4 ± 0.1	$0.6 \pm 0.2^{\wedge}$
Noradrenaline ($nmol.L^{-1}$)	2.0 ± 0.4	$14.3 \pm 9.4^{*\wedge}$	1.6 ± 0.6	$3.0 \pm 1.1^{\wedge}$

[*] Denotes significantly higher than the corresponding data point in the simulated combat condition; $P < 0.05$. ^ Denotes significant increase from the pre sampling period in the same combat condition; $P < 0.05$.

4.2.4 Discussion

The aim of this investigation was to compare the physiological and stress hormonal responses to performing Taekwondo combats in simulated and championship settings. The main findings of this investigation demonstrate that championship Taekwondo combats augment the physiological (e.g. HR, plasma lactate, glucose and glycerol) and hormonal responses (e.g. adrenaline and noradrenaline) in comparison to simulated combats performed in a controlled setting. Interestingly, these contrasting responses were evident even though both combat settings exhibit comparable activity profiles (Chapter 4.1). The same participants, warm up protocol and nutritional practices were also used in both combat settings. The incongruent physiological demands induced by these combat settings may therefore be attributed to factors other than differences in physical workload, fitness status and energy intake. In agreement with the hypothesis, the reduced physiological responses in the Taekwondo simulation seemed to be mediated by the increased stress responses in competition.

Both the simulated and championship Taekwondo combats induced a significant rise in plasma adrenaline and noradrenaline concentrations. This would suggest that both combat conditions stimulated sympathetic nerve activity and adrenal medulla chromaffin cell exocytosis facilitating the release of catecholamines into the circulation (Goldstein, Eisenhofer & Kopin, 2003; Zouhal *et al.*, 2008). While both of these combat settings elevated the circulating levels of catecholamines, the magnitude of this increase was greater in the championship combats. The rise in both plasma adrenaline and noradrenaline was nearly five-fold higher in the championship Taekwondo combats than in the simulated Taekwondo combats. This response would suggest that the championship Taekwondo combats evoked greater sympathetic nerve activity and adrenal medulla exocytosis resulting in an increased catecholamine spillover into the circulation (Zouhal *et al.*, 2008). This is consistent with the view that plasma adrenaline and noradrenaline concentrations determined during intense exercise are more a reflection of higher catecholamine secretory mechanisms as opposed to a reduction in their elimination (Zouhal *et al.*, 1998; Zouhal *et al.*, 2001; Moussa *et al.*, 2003; Zouhal *et al.*, 2008).

Plasma catecholamines in concert to several allosteric activators assist in the regulation of a number of cardiovascular and metabolic processes by acting on both α and β adrenergic receptor sites. Noradrenaline primarily activates α-receptors and adrenaline may activate both α and β-receptors (Garcia-Sainz, 1995). The release of adrenaline and noradrenaline into the circulation during exercise act simultaneously on these receptor sites to stimulate numerous cardio-respiratory and metabolic functions such as HR, cardiac output, glycogenolysis, glycolysis, carbohydrate oxidation and lipolysis (Febbraio *et al.*, 1998; Watt *et al.*, 2001; Kreisman, Halter, Vranic & Marliss, 2003;

Watt, Stellingwerff, Heigenhauser & Spriet, 2003; Zouhal *et al.*, 2008). It is therefore conceivable that the higher HR, plasma lactate, glucose and glycerol concentrations in the championship combats were actualised, in part, by greater sympathetic-adrenal-medulla (SAM) activation, increased release of catecholamines into the circulation and enhanced adrenoceptor stimulation (Zouhal *et al.*, 2008). More precisely, the increased plasma lactate and catecholamine concentrations in the championship combats may reflect greater catecholamine-mediated activation of glycolysis and glycogenolysis through enhanced glycogen phosphorylase activity (Hoch *et al.*, 1988; Febbraio *et al.*, 1998; Watt *et al.*, 2001). This process is primarily mediated via increased binding of adrenaline to sarcolemmal β-adrenergic receptors, which activate adenylate cyclase to synthesise 3,5-cyclic adenosine monophosphate (cAMP) (Watt *et al.*, 2001). This cAMP cascade sequentially activates protein kinase-A, phosphorylase kinase and phosphorylase to stimulate muscle glycogenolysis (Febbraio *et al.*, 1998; Watt *et al.*, 2001). The concomitant elevation in plasma glucose and catecholamines in the championship combats are suggestive of enhanced catecholamine-activation of hepatic glycogenolysis (Kreisman *et al.*, 2000; Kreisman *et al.*, 2003). This response is initiated by increased binding of adrenaline to both α and β adrenoceptors in the liver, which activate both the phosphoinositide and cAMP cascades resulting in phosphorylase-a activation of hepatic glycogenolysis (Kreisman *et al.*, 2000). The greater plasma glycerol and catecholamine concentrations in the championship combats are characteristic of increased catecholamine-mediated activation of lipolysis (Arner, Kriegholm, Engfeldt & Bolinder, 1990; Horowitz, 2003). This hormonal control of lipolysis is augmented through adrenaline and noradrenaline binding to adipocyte β-adrenergic receptors, which activate the cAMP cascade. This process stimulates cAMP-dependent protein kinase to phosphorylate and activate perilipin, and hormone sensitive lipase (HSL) resulting in accelerated lipolytic rate (Horowitz, 2003).

The catecholamine responses to exercise may be regulated by a number of physical and non-physical mediators such as physical workload (intensity) (Tatar *et al.*, 1984; Jezova *et al.*, 1985), fitness status (Zouhal *et al.*, 2001), nutritional intake (Langfort *et al.*, 1997) and psychological stress (Gerra *et al.*, 2001; Webb *et al.*, 2008). It seemed necessary, therefore, to determine the primary factors that mediate the incongruent catecholamine responses in these simulated and championship Taekwondo combat settings. The simulated Taekwondo combats provided a close approximation of the activity profile performed in championship combats (Chapter 4.1). This would imply that both combats induced comparable physical workloads. The impacts typically received from an opponent in the championship combats were, however, excluded from the simulated combats in this study. This oversight has been recognised as a physical factor that may contribute to the reduced energetic requirements in this simulated combat setting (Chapter 4.1). In contrast to this notion, full-contact forms of simulated Taekwondo combat (e.g. that include the impacts typically received from an opponent) also demonstrate a propensity for reduced physiological responses in comparison to championship combats (Chapter 3.3) (Butios & Tasika, 2007). As such, these data collectively suggest that variation in the physical workload is not the primary factor mediating the dissonant physiological and hormonal responses to the simulated and championship Taekwondo combats.

Variation in the competitors' fitness status and nutritional practices leading up to combat may potentially modulate the catecholamine responses in the simulated and championship combats (Langfort *et al.*, 1997; Zouhal *et al.*, 2001). The stringent preparations leading up to the actual championship event meant that the participants were unavailable for maximal physical capacity testing in the laboratory. As such, an appraisal of the participants' physical capabilities was not undertaken during the course of the study. The same participants were, however, examined in both combat conditions and each combat was separated by a period of two weeks. The participants' were also instructed to maintain similar training loads in the period leading up to each combat. This experimental approach would mitigate the possibility of significant alterations in the competitors' physical capabilities during this period. The competitors were also instructed to replicate the same nutritional practices and attain a similar body weight (at the weight-in) in both the simulated and championship combats. These control measures may therefore exonerate variation in competitors' fitness status and nutritional practices as key mediators of the disparate catecholamine responses in the simulated and championship combats.

It is well established that a range of acute psychological stressors can activate the SAM and the hypothalamic-pituitary-adrenocortical (HPA) axis facilitating the release of stress hormones catecholamines and cortisol into the circulation (Gerra *et al.*, 2001; Erickson *et al.*, 2003; Gaab, Rohleder, Nater & Ehlert, 2005; Goldstein & Kopin, 2008). This process or 'stress response' augments numerous cardio-respiratory and metabolic functions at rest and during exercise (Richter *et al.*, 1996; Watt *et al.*, 2001; Viru & Viru, 2004; Goldstein & Kopin, 2008; Webb *et al.*, 2008; Rimmele *et al.*, 2009; Huang *et al.*, 2010). The mechanisms by which the release of these hormones regulates specific metabolic processes have been detailed earlier in this chapter. The higher physiological strain identified before, during and after the championship combats in comparison to the simulated combats may therefore be a function of the greater stress responses in the moments before and during the championship combats. The significantly higher catecholamine concentrations measured after the championship combats in comparison to the simulated combats would support the notion of greater stress responses during the course of the championship combats. Especially since variations in the physical workload, fitness status and nutritional practices are not able to explicate these hormonal responses. In contrast, no significant differences in the pre combat plasma catecholamine concentrations were identified between the simulated and championship combats. This finding could suggest similar stress responses in the moments before the simulated and championship combats, but it is more likely to reflect the plasma catecholamine sampling times. The pre combat samples were collected on average nine minutes prior to commencing combat in both settings. Plasma catecholamines increase rapidly in response to both psychological and physical stressors and their half-life is typically between one and two minutes (Labrosse, Mann & Kety, 1961; Silverberg, Shah, Haymond & Cryer, 1978; FitzGerald *et al.*, 1979). The peak plasma catecholamine concentrations may therefore have been missed in the pre combat sampling periods (Richter *et al.*, 1996). Nevertheless, significantly higher plasma cortisol concentrations have been identified in the moments before (1 to 4 hours) and after championship Taekwondo combats than during the equivalent periods of simulated combat (Obminski, 2008). These data collectively provide compelling evidence to suggest that dissonant stress hormonal responses may be the principle factor mediating the disparate metabolic function in these simulated and championship Taekwondo combats.

4.2.5 Conclusions and Practical Applications

The main findings of this investigation demonstrate that championship Taekwondo combats augment the physiological and hormonal responses in comparison to simulated combats performed in a controlled setting. Interestingly, these contrasting responses were evident even though both combat settings exhibit comparable activity profiles (Chapter 4.1). The same participants, warm up protocol and nutritional practices were also used in both combat settings. As such, the incongruent physiological demands induced by these combat settings may be attributed to factors other than differences in physical workload, fitness status and energy intake. These seem to be mediated by the stress hormonal responses to fighting in championship events. This suggests that both the physical workload of the combat activity and the stress responses to fighting may play an integral role in regulating metabolic function in Taekwondo combat. This evidences the particular relevance of adopting a psychophysiological approach in the preparation of Taekwondo competitors for competition.

CHAPTER 5

PHYSIOLOGICAL AND HORMONAL RESPONSES TO A SIMULATED TAEKWONDO EVENT

5.1 PHYSIOLOGICAL AND HORMONAL RESPONSES TO SUCCESSIVE TAEKWONDO COMBATS

5.1.1 Introduction

Recent research into the physiological demands of Taekwondo competition has resulted in significant advances in our understanding of the energetic requirements of a single Taekwondo combat (Chapters 3.1 & 4.2) (Heller *et al.*, 1998; Chiodo *et al.*, 2009; Matsushigue *et al.*, 2009; Pilz-Burstein *et al.*, 2010). During a Taekwondo championship event, however, successful competitors may be required to compete in a number of combats during a single day with variable recovery intervals separating each match. Few attempts have been made to examine the physiological, hormonal and performance responses to this phenomenon in combat sports (Kraemer *et al.*, 2001; Pilz-Burstein *et al.*, 2010). In combat sports such as Wrestling, performing repeated combats across a single day or several days modulates the physiological and hormonal responses, and down regulates a number of physical performance capabilities (Kraemer *et al.*, 2001). The physiological and hormonal responses to performing repeated Taekwondo combats have been examined in adolescent male competitors (Pilz-Burstein *et al.*, 2010). Performing three repeated Taekwondo combats interspersed with thirty-minute recovery intervals resulted in significant attenuations in plasma lactate, testosterone, free androgen index, LH, FSH and IGF-I, and increases in plasma cortisol. These hormonal adjustments speak in favour of enhanced protein catabolic processes as the combats were repeated (Pilz-Burstein *et al.*, 2010).

There have been no attempts to quantify the physiological and hormonal responses to performing repeated Taekwondo combats in senior male international level competitors. Competitors' age and gender modulate the physiological and hormonal responses to high intensity exercise (Boisseau & Delamarche, 2000; Zouhal *et al.*, 2008; Pilz-Burstein *et al.*, 2010; Hackney *et al.*, 2011). This would suggest that the available data on male adolescent Taekwondo competitors may not be generalisable to other populations of Taekwondo competitors. As such, further research into the physiological and hormonal responses to performing repeated Taekwondo combats in senior male international level competitors would seem necessary. The rest interval between each combat may also mediate the physiological and hormonal responses to combat and influence the recovery of a number of metabolites (Degoutte *et al.*, 2003; Stokes *et al.*, 2005; Burnley *et al.*, 2006; Goto *et al.*, 2007; Bailey *et al.*, 2009). No attempts have been made to examine the physiological and hormonal responses to successive Taekwondo combats using an ecologically valid competition time structure. The aim of this study was to examine the physiological and hormonal responses to performing successive Taekwondo combats, in senior male competitors, using an ecologically valid competition time structure. It was hypothesised that performing successive Taekwondo combats in an ecologically valid time structure would modulate the physiological and hormonal responses to combat and perturb homeostasis between the combats.

5.1.2 Methods

5.1.2.1 Participants

Ten male Taekwondo black belts (mean $\pm$ SD, age 19 $\pm$ 3 years, body mass 62.3 $\pm$ 2.6 kg, height 1.72 $\pm$ 0.04 m, competition experience 6 $\pm$ 1 years) took part in this study. The sample comprised senior international level competitors from the British national team and British technical centres that had obtained significant results (medals) during international events. The participants were regularly competing in various WTF sanctioned international level events (e.g. Olympic Games, European Championships and European Taekwondo Union A-class international events), under different weight categories. More precisely, the sample included competitors from Bantam -63 kg (n = 5) and feather –67 kg (n = 5) weight divisions. The participants were informed of the test procedures and potential risks, and written informed consent was obtained. The study was approved by an Institutional Research Ethics Committee.

5.1.2.2 Experimental Design

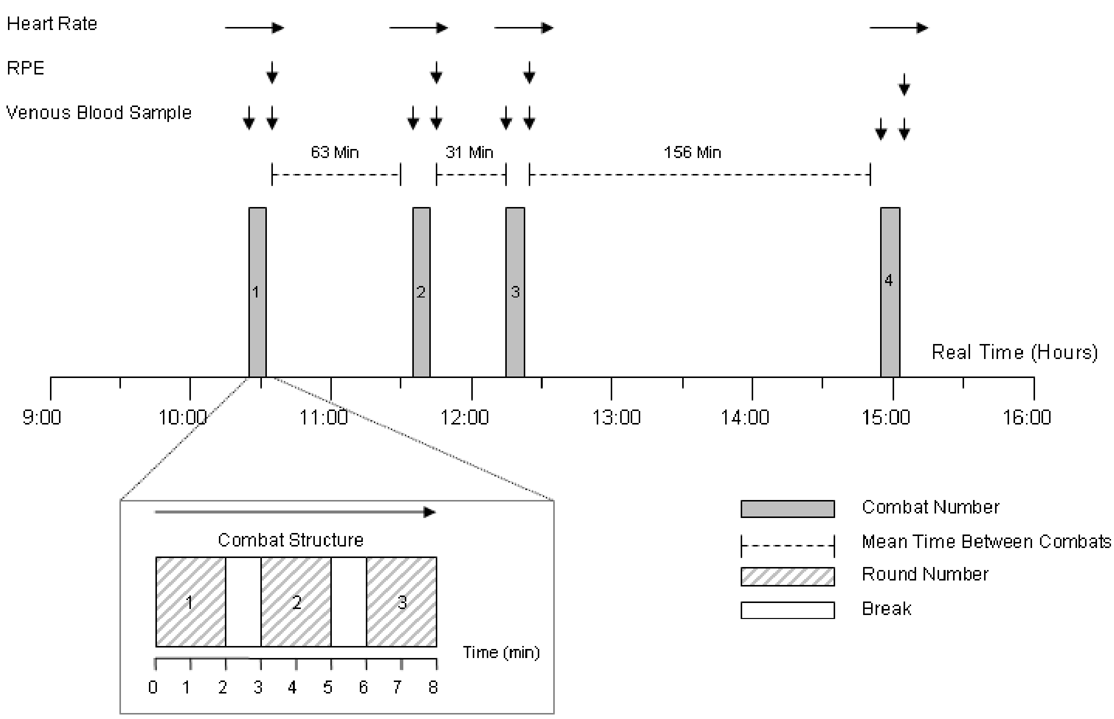
The participants took part in a simulated Taekwondo championship event that was structured according to WTF regulations. The simulated championship event incorporated a 'test match' configuration. During a test match event Taekwondo competitors' compete in a number of full-contact combats across a single day. These combats are contested against high-level unfamiliar exponents in the presence of a large volume of peers and coaches. This test match concept is often employed by experienced international coaches to maximise the physiological, technical, tactical and psychological demands on the athletes during practice combats. It also serves as a useful tool to gauge an athlete's progress at particular time points throughout the training calendar. This experimental paradigm was selected after careful consideration of a number of factors. An actual championship event would be ecologically favourable to quantify the physiological and hormonal responses to performing repeated combats (Chapter 4.2) (Chiodo *et al.,* 2009). A range of constraints were, however, identified that precluded the implementation of this strategy. Such difficulties include the problems associated with performing repeated venipunctures in this setting, the increased likelihood of missing the peak plasma catecholamine concentrations (Chapter 4.2) and the inability to provide appropriate experimental control of the time interval between each combat. As such, it was viewed that a simulated championship event would be suitable to not only circumvent these factors but also provide a suitable experimental model for the investigation. Though it is acknowledged that this experimental paradigm may elicit reduced physiological and hormonal responses than equivalent championship Taekwondo combats, it is a better approximation of the physiological demands of these types of events than using laboratory-based simulations (Chapter 4.2). In a number of combat sports, full-contact simulations of combat provide close approximations of the activity profiles, and the physiological and hormonal responses elicited in championship combats (Ghosh *et al.*, 1995; Kraemer *et al.*, 2001; Bouhlel *et al.*, 2006; Franchini *et al.*, 2009; Artioli *et al.*, 2010; Pilz-Burstein *et al.*, 2010). This approach has also been used effectively to study the influence of interventions on the combat demands (Kraemer *et al.*, 2001; Franchini *et al.*, 2009; Barbas *et al.*, 2010).

5.1.2.3 Simulated Competition Procedures

The participants competed in a test match event that was staged inside a gymnasium, on standard mats, using two combat areas that conformed to the WTF regulations (Figure 2.2.1). To ensure that a suitable sample (n = 10) could be analysed and that the timing of the matches could be adequately controlled, the data were collected from two separate test match events that implemented the same format. Each test match event was organised across a single day between the hours of 9:00 and 18:00 in an attempt to recreate the structure of an international championship event (Figure 3.1.1). Three separate international Taekwondo events (Swedish International Open, Trelleborg, Sweden, 2006; Dutch International Open, Eindhoven, Holland, 2008; and the British International Open, Manchester, England, 2008) were initially examined to determine the typical number of combats performed by the competitors while progressing towards their final match. The typical range of combats performed by the competitors were 3-4, 3-5 and 3-5 for the Swedish, Dutch and British international events, respectively. The participants were therefore asked to compete in four separate combats during the test match event in this study to provide some ecological validity to the design. This choice was a compromise between representing the maximum range of combats typically performed during competition and satisfying the participants' desire to engage in invasive data collection procedures on repeated occasions (e.g. repeated venipuncture). The recovery intervals between the combats were also structured in consideration of the intermissions measured during the Swedish, Dutch and British international events. The mean $\pm$ SD recovery intervals between the combats were 72 $\pm$ 60, 85 $\pm$ 46 and 88 $\pm$ 61 minutes for the Swedish (n = 12), Dutch (n = 25) and British (n = 20) international events, respectively. The minimum and maximum recovery intervals recorded between the combats were 14 to 211, 22 to 226 and 31 to 227 minutes for the Swedish, Dutch and British international events respectively. As such, the combats in the test match event were structured with the intent of replicating a range of these durations (e.g. mean, minimum and maximum data). The high ecological validity of the test match events meant that the combats were performed at variable time intervals during each day. The mean ± SD start 'real' times for the combined events were 10:23 ± 00:20, 11:35 ± 00:19, 12:15 ± 00:21 and 14:58 ± 00:21 hours:minutes for combats 1, 2, 3 and 4, respectively. The mean ± SD time between combats 1 and 2, 2 and 3, and 3 and 4 for the combined events were 63 ± 4, 31 ± 3, and 156 ± 5 minutes, respectively (Figure 5.1.1). The recovery time between the combats was calculated as the period between finishing the final round of combat and commencing the first round of the subsequent combat. Each combat comprised three rounds of two-minutes with one-minute recovery between each round (Figure 5.1.1).

Prior to competing in the test match event, each participant's body mass was assessed to determine their fighting weight division. Only competitors from the same weight division were permitted to compete against each other during each event. During the event, the participants' were only permitted to consume water (ad libitum). The unfamiliar opponents provided for the sample during the test match event were high-level international competitors from the French and Korean national teams, and British technical centres. To maximise the ecological validity of the events, matches were governed by qualified international level referees and the match score was publicised during the event. The ambient temperature and humidity was recorded next to each competition area at 9:00, 13:00 and 18:00 hours using a Whirling Psychrometer (G.H. Zeal Ltd, London UK). The mean ± SD temperature and humidity for the events were 22 ± 3 ^{o}C and 22 ± 3 %, respectively.

Figure 5.1.1: Schematic representation of the competition day



5.1.2.4 Physiological, Hormonal and RPE Procedures

Heart rate was recorded at 5 s intervals during each of the four combats to assess the relative cardiovascular strain (See Chapter 3.1.2.2 for further details of this procedure). The participants' HRmax was calculated as the highest value obtained during the event (Chapters 3.1.2.2 and 4.2.2.5). Ratings of perceived exertion were used as an additional methodology to describe and monitor the intensity of the four combats (Chapter 3.1.2.2). Venous blood samples were obtained immediately before and after each of the four combats to determine the plasma concentrations of lactate, glucose, glycerol, NEFA, adrenaline and noradrenaline (Chapter 4.2.2.5). Due to the greater control over the combat start times during each event, blood sampling was typically complete < 1.5 minutes before and after each combat. The data inclusion criteria were the successful attainment of HR, RPE and venous blood samples across four combats performed in the time structure outlined in figure 5.1.1.

5.1.2.5 Biochemical Analysis

Plasma lactate, glucose, glycerol and NEFA were analysed using a fully automated random access clinical analyser (RX Daytona, Randox Laboratories Ltd, UK). Lactate was analysed via the enzymatic method, glucose via the glucose oxidase phenol 4-aminoantipyrine peroxidise method (GOD-PAP), NEFA using the colorimetric method and glycerol using the glycerol-3-phosphate oxidase phenol 4-Aminoantipyrine peroxidase (GPO-PAP, Randox Laboratories Ltd, UK) method. Solid phase enzyme-linked immunosorbent assay (ELISA) was used for quantitative determination of adrenaline and noradrenaline using the manual procedure (CatCombi ELISA, IBL International, Hamburg, Germany). All of the samples were analysed in duplicate and the intra-assay CV's for lactate, glucose, glycerol and NEFA were < 2 %, and for catecholamines < 6 %.

5.1.2.6 Statistical Analysis

The mean $\pm$ SD data were calculated for each variable. All of the data were assessed for normality using Shapiro-Wilks test prior to analysis. A one-way repeated measures ANOVA was performed on the mean HR and recovery HR data (mean of round 1, 2 and 3 for each combat) to identify differences in these parameters between the combats. A two-way (time [precombat, round 1, 2 and 3] x combat [1, 2, 3 and 4]) repeated measures ANOVA was performed on the HR and RPE variables to permit more detailed examination of the data between the rounds and combats. A two-way (time [pre and post combat] x combat [1, 2, 3 and 4]) repeated measures ANOVA was performed upon the plasma metabolite and hormone variables. Where appropriate, multiple comparisons using Bonferroni interval adjustment were employed to determine which particular levels of a factor were significantly different from each other (Atkinson, 2002). Statistical significance was set at $P < 0.05$.

5.1.3 Results

5.1.3.1 Cardiovascular and RPE responses

The mean HR and RPE data for each individual combat are presented in Table 5.1.1. The one-way ANOVA's identified differences in the mean recovery HR ($P < 0.001$) and the recovery %HRmax ($P < 0.001$) between the combats, with significantly higher values elicited in combats 3 and 4 in comparison with combats 1 and 2 (Table 5.1.1). No differences in the mean HR ($P = 0.13$) and % HRmax ($P = 0.16$) were identified between the four combats using this statistical technique (Table 5.1.1).

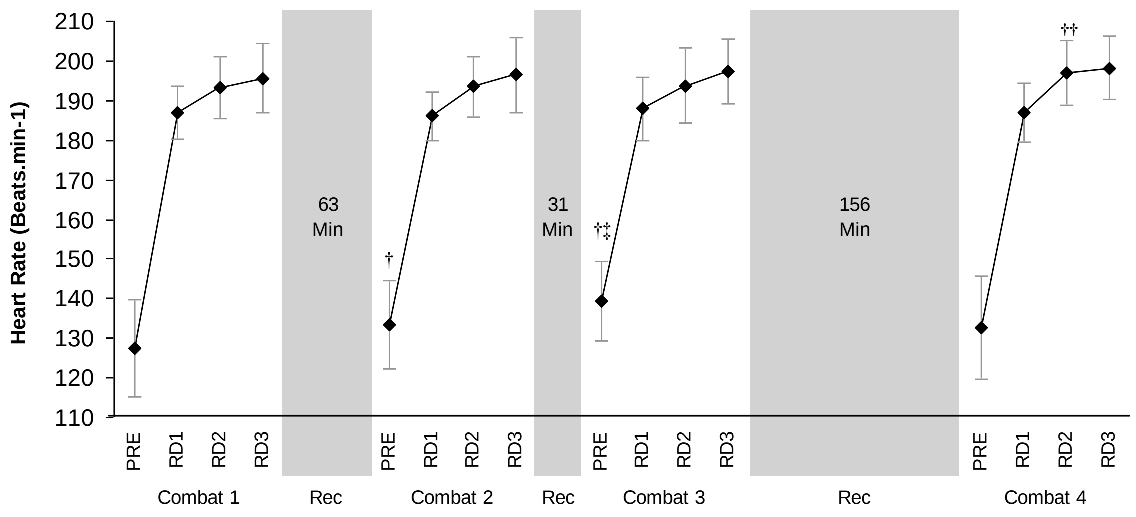
The two-way ANOVA identified significant main effects for combat ($P = 0.002$) and time ($P < 0.001$), and an interaction between combat and time for HR ($P < 0.001$). Post hoc analysis identified a successive increase in the pre-combat HR between combats 1 and 3 (127 to 139 beats.min^{-1}) (Figure 5.1.2). As a consequence, the increase in HR from the pre-combat period to round 1 was greater in magnitude in combat 1 (127 to 187 beats.min^{-1}) in comparison with combats 2 (133 to 186 beats.min^{-1}) and 3 (139 to 188 beats.min^{-1}) (Figure 5.1.2). The increase in HR between round 1 and 2 was greater in magnitude in combat 4 (187 to 197 beats.min^{-1}) compared with combat 1 (187 to 193 beats.min^{-1}; $P = 0.012$) and combat 3 (188 to 194 beats.min^{-1}; $P = 0.036$), but this difference was not statistically significant in combat 2 ($P = 0.10$) (Figure 5.1.2). There was a significant main effect for time for RPE ($P < 0.001$), with RPE increasing between round 1 and 2 ($P < 0.001$) and between round 2 and 3 ($P = 0.001$) in each of the four combats (Figure 5.1.3). The main effect for combat for RPE ($P = 0.421$) and the interaction between combat and time ($P = 0.498$) were not statistically significant (Figure 5.1.3).

Table 5.1.1: Mean ± SD heart rate and RPE data for each of the four combats

	Combat 1		Combat 2		Combat 3		Combat 4
Time Between Combats		63 Min		31 Min		156 Min	
Combat HR (beats.min^{-1})	192 ± 8		192 ± 8		193 ± 8		194 ± 8
Combat HRmax (%)	94 ± 1		94 ± 1		94 ± 1		94 ± 1
Recovery HR (beats.min^{-1})	175 ± 10		176 ± 10		180 ± 10†		183 ± 9†‡
Recovery HRmax (%)	85 ± 3		86 ± 2		88 ± 2†		89 ± 2†‡
Combat RPE	13 ± 1		13 ± 1		14 ± 2		13 ± 2

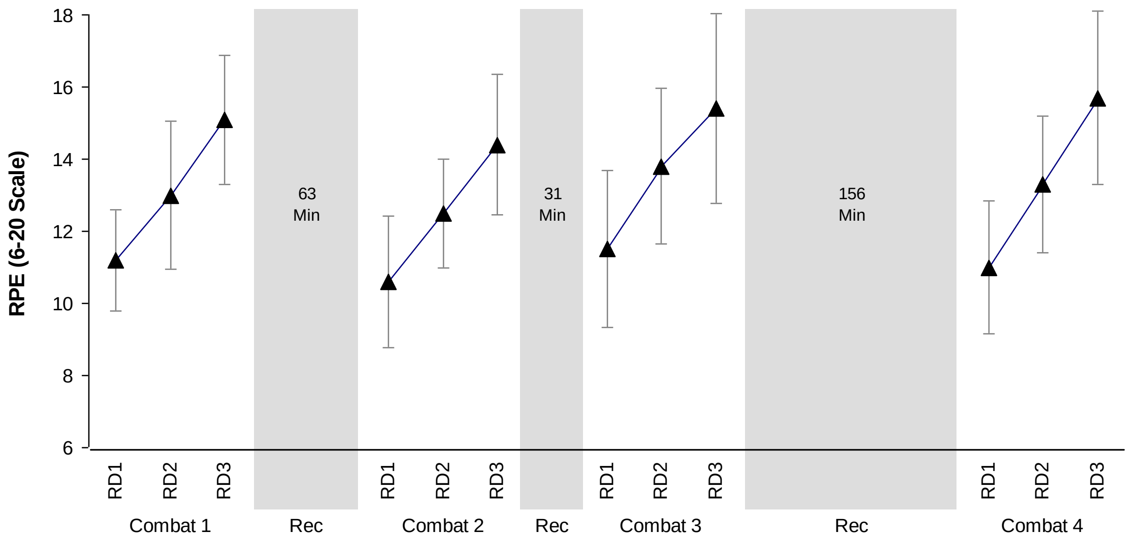
† Denotes significantly higher than combat 1, $P < 0.05$. ‡ Denotes significantly higher than combat 2, $P < 0.05$. Shaded values represent the mean recovery time (minutes) between each combat. Recovery HR represents the HR responses during the one-minute recovery intervals between each of the three rounds of combat.

Figure 5.1.2: Mean ± SD heart rate responses between the rounds and combats



† Denotes significantly higher than the corresponding time point in combat 1, $P < 0.05$. ‡ Denotes significantly higher than the corresponding time point in combat 2, $P < 0.05$. †† Denotes significantly higher than the corresponding time point in combats 1 and 3, $P < 0.05$. Rec. Denotes the mean recovery time in minutes between combats.

Figure 5.1.3: Mean ± SD RPE between the rounds and combats



Rec. Denotes the mean recovery time in minutes between combats.

5.1.3.2 Plasma Metabolites

The mean plasma metabolite data for each of the four combats are presented in Table 5.1.2. There was a significant main effect for combat (P = 0.021) and time (P < 0.001), and an interaction (P = 0.022) between combat and time for plasma lactate (Table 5.1.2). Plasma lactate concentrations were significantly higher in the pre sampling period in combat 3 compared with combat 1 (P = 0.021) and 4 (P = 0.015) (Table 5.1.2). No difference in the pre sampling plasma lactate concentrations were evident between combat 3 and combat 2 (P = 0.91). The increase in plasma lactate between the pre and post sampling period was greater in magnitude in combat 1 compared with combat 4 (mean increase of 11.9 vs. 8.6 $mmol.l^{-1}$; P = 0.009) (Table 5.1.2). There was a significant main effect for time (P < 0.001) and a significant interaction between combat and time (P = 0.022) for plasma glucose, but the main effect for combat was not significant (P = 0.41) (Table 5.1.2). The significant rise in plasma glucose between the pre and post sampling periods was more pronounced in combat 1 (3 $mmol.l^{-1}$ increase; P < 0.001) and combat 4 (2.5 $mmol.l^{-1}$ increase; P < 0.001) compared with combat 3 (1.6 $mmol.l^{-1}$ increase; P = 0.004) (Table 5.1.2). A significant increase in plasma glucose between the pre and post sampling periods was absent in combat 2 (P = 0.60), resulting in significantly lower post combat glucose concentrations compared with combat 1 (Table 5.1.2).

There were significant main effects for combat (P = 0.008) and time (P < 0.001) for plasma glycerol, but the interaction between combat and time was not statistically significant (P = 0.214) (Table 5.1.2). Plasma glycerol concentrations were significantly higher in combat 3 compared with combat 1 (P = 0.038) and combat 2 (P = 0.037) (Table 5.1.2). A significant main effect was identified for combat for plasma NEFA (P = 0.011), but the main effect for time (P = 0.74) and the interaction between combat and time (P = 0.55) were not statistically significant (Table 5.1.2). Plasma NEFA concentrations were significantly higher in combat 3 compared with combat 1 (P = 0.011) and combat 2 (P = 0.006) (Table 5.1.2).

5.1.3.3 Plasma Hormones

The mean plasma hormone data for each of the four combats are presented in Table 5.1.2. There was a significant main effect for combat for adrenaline (P = 0.04), but the main effect for time (P = 0.60) and the interaction between combat and time (P = 0.58) were not statistically different. Plasma adrenaline concentrations were significantly higher in combat 3 compared with combat 2 (P = 0.01), with no differences apparent between the remaining combats (Table 5.1.2). Significant main effects for combat (P = 0.008) and time (P = 0.001), and a significant interaction between combat and time (P = 0.009) were identified for plasma noradrenaline (Table 5.1.2). The rise in plasma noradrenaline between the pre and post sampling periods was greater in magnitude in combat 1 compared with combat 2 ($P = 0.018$) and combat 3 ($P = 0.027$), and there was a trend for higher values in comparison with combat 4 ($P = 0.06$) (Table 5.1.2).

Table 5.1.2: Mean ± SD plasma metabolite and hormone data across the combats

	Combat 1		Combat 2		Combat 3		Combat 4	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Time Between Combats		63 Min			31 Min		156 Min	
Lactate (mmol.l^{-1})	2.0 ± 0.7	13.9 ± 4.2*	2.8 ± 0.9	10.9 ± 3.7*	3.1 ± 1.2$^{\dagger\wedge}$	11.6 ± 3.4*	1.9 ± 0.8	10.5 ± 3.2$^{\dagger *}$
Glucose (mmol.l^{-1})	6.1 ± 0.8	9.1 ± 1.4*	6.7 ± 1.5	7.8 ± 1.9†	6.2 ± 1.7	7.8 ± 2.1*	5.6 ± 1.7	8.1 ± 1.8*
NEFA (mmol.l^{-1})	0.71 ± 0.28	0.68 ± 0.25	0.69 ± 0.27	0.78 ± 0.33	0.95 ± 0.29†‡	0.96 ± 0.27†‡	0.82 ± 0.35	0.81 ± 0.28
Glycerol (µmol.l^{-1})	56 ± 38	137 ± 60*	95 ± 70	166 ± 92*	131 ± 83†‡	202 ± 104$^{\dagger\ddagger *}$	83 ± 50	141 ± 49*
Adrenaline (nmol.l^{-1})	11.5 ± 4.6	14.1 ± 6.1	11.7 ± 7.4	12.1 ± 6.3	8.9 ± 5.7‡	9.5 ± 5.0‡	10.4 ± 8.4	9.6 ± 5.7
Noradrenaline (nmol.l^{-1})	7.7 ± 1.9	21.8 ± 10.3*	8.3 ± 2.8	15.2 ± 6.3$^{\dagger *}$	7.5 ± 1.2	15.3 ± 5.6$^{\dagger *}$	8.3 ± 2	16.1 ± 8.0$^{\S *}$

† Denotes significantly different than the corresponding data point in combat 1, $P < 0.05$. ‡ Denotes significantly different than the corresponding data point in combat 2, $P < 0.05$. ^ Denotes significantly different than the corresponding data point in combat 4; $P < 0.05$. § Denotes a trend ($P = 0.06$) lower values compared with combat 1. * Denotes a significant increase from the pre combat period in the corresponding combat, $P < 0.05$. Shaded values represent the mean recovery time (minutes) between each combat.

5.1.4 Discussion

The purpose of this study was to examine the physiological and hormonal responses to performing successive Taekwondo combats, in senior male competitors, using an ecologically valid competition time structure. In agreement with the hypothesis, the primary findings of this study demonstrate that performing repeated Taekwondo combats in an ecologically valid time structure modulates the physiological and hormonal responses to combat and perturbs homeostasis between the combats. Most notably, the successive combats resulted in reduced plasma noradrenaline and lactate responses to combat and increased HR responses earlier in combat. Importantly, the HR and plasma concentrations of glycerol, NEFA and lactate remained elevated above baseline levels between a number of the repeated combats. These findings emphasise the relevance of strategies to facilitate the recovery process and enhance energy availability between repeated combats in championship events.

Prior to discussing the key findings of the study there is value in highlighting the external validity of the physiological and hormonal responses elicited by the test match combats. The mean HR responses, and plasma lactate, glycerol and NEFA concentrations elicited in the initial test match combats correspond with those measured in international championship combats (Chapter 3.1 & Chapter 4.2). This would suggest that the test match combats in this study provide an accurate and valid representation of the physiological demands of championship Taekwondo combats. The pre and post sampling plasma adrenaline and noradrenaline concentrations in the test match combats were, however, remarkably higher than those measured in the championship combats (Chapter 4.2). This finding could imply discordant sympathetic-adrenal-medullar (SAM) activation in these settings (Eisenhofer, Kopin & Goldstein, 2004), but it is more likely to reflect the variation in the plasma sampling times between these investigations (Dimsdale & Moss, 1980; Richter *et al.*, 1996). The average pre and post plasma sampling times in the international championship combats were nine and four minutes respectively (Chapter 4.2). Plasma sampling was typically complete within 1.5 minutes before and after each test match combat in the present study due to the greater experimental control offered by this setting. Plasma catecholamines increase rapidly in response to both psychological and physical stressors and their half-life is typically between one and two minutes (Labrosse *et al.*, 1961; Silverberg *et al.*, 1978; FitzGerald *et al.*, 1979). It is therefore conceivable that the variation in the plasma sampling periods were responsible for the disparate catecholamine concentrations observed between these combat settings. As such, test match events may not only provide an accurate representation of the physiological demands of championship Taekwondo combats, but this experimental paradigm may also offer greater control of key variables to enable more accurate depictions of the combat hormonal responses.

The successive Taekwondo combats in this study resulted in increased cardiovascular demands both before and during several combats. The pre combat HR increased sequentially between combats 1 and 3 (e.g. 127 to 139 beats.min^{-1}). This response may reflect the rapid and prolonged components of 'excess post-exercise oxygen consumption' (EPOC) incurred from the preceding combats, and suggest that the recovery processes were largely incomplete following the 63 and 31 minute intervals between these combats (Borsheim & Bahr, 2003; Sedlock, Lee, Flynn, Park & Kamimori, 2010). The elevated $\dot{V}O_2$ and HR involved in the rapid component of EPOC following brief intense intermittent exercise is largely a consequence of the aerobic ATP required to replenish phosphocreatine (PCr), restore oxygen to the myoglobin and haemoglobin, oxidise lactate and reconvert lactate to glucose via gluconeogenesis in the Cori-cycle (Borsheim & Bahr, 2003). In contrast, the aerobic ATP fuelling the prolonged component of EPOC is thought to be mediated primarily by enhanced rates of triglyceride and fatty acid cycling, and/or muscle protein degradation and synthesis (Borsheim & Bahr, 2003). The elevated plasma concentrations of NEFA, glycerol and lactate measured in the pre sampling period in combat 3 would support the notion that the rapid and prolonged components of EPOC were incomplete following the 31 minute recovery period (Dodd, Powers, Callender & Brooks, 1984; Mulla, Simonsen & Bulow, 2000). Interesting, however, elevated plasma concentrations of NEFA, glycerol and lactate, and increased HR was absent from the pre sampling period in the final combat. This may be a consequence of the more lengthy rest interval between combat 3 and 4 (e.g. 156 minutes) permitting more complete restoration of homeostatic control. This finding highlights the value of adopting strategies to facilitate the recovery processes when shorter rest intervals are anticipated between the combats in championship events.

The HR data also suggest that successive combats increased the cardiovascular demands during combat. In the final combat, the increase in HR between round 1 and 2 was greater in magnitude in comparison with combats 1, 2 and 3. This response suggests increased cardiovascular demands earlier in combat 4. The increased HR response during the final combat may be a function of a change in the activity levels of the competitors' and/or altered metabolic function as a result of performing successive combats. In support of the latter concept, research consistently reports increased reliance on aerobic metabolism to fuel contractile activity as high intensity bouts are repeated (Gaitanos *et al.*, 1993; Bogdanis, Nevill, Boobis & Lakomy, 1996; Parolin *et al.*, 1999). This response is often a consequence of adjustments in muscle metabolites and/or increased HR and $\dot{V}O_2$ kinetics (Gaitanos *et al.*, 1993; Bogdanis, Nevill, Boobis & Lakomy, 1996; Wilkerson, Koppo, Barstow & Jones, 2004; Burnley *et al.*, 2006). The recovery HR between the rounds also tended to be higher in the final two combats compared with the initial two combats. This observation is consistent with the increased EPOC response that occurs as exercise bouts are repeated (Ballor & Volovsek, 1992; Balsom, Seger, Sjodin & Ekblom, 1992; Miladi, Temfemo, Mandengue & Ahmaidi, 2011). This is often a function of the combined actions of the increased HR and $\dot{V}O_2$ kinetics during the exercise bouts and the increased aerobic ATP required to fuel the recovery processes that are incurred from multiple O_2 deficits (Gaitanos *et al.*, 1993; Dorado, Sanchis-Moysi & Calbet, 2004; Bailey *et al.*, 2009; Miladi *et al.*, 2011). Regardless of the mechanisms involved, these data suggest that performing repeated Taekwondo combats augments the cardiovascular demands during each combat.

A significant rise in plasma lactate was evident between the pre and post sampling periods in each of the four combats, which is indicative of enhanced glycolytic activity (Gaitanos *et al.*, 1993). The rise in plasma lactate was, however, attenuated in the final combat compared with the first combat. A trend for reduced plasma lactate responses while performing repeated combats has also been observed in adolescent Taekwondo competitors and in other combat sports such as Wrestling and Judo (Kraemer *et al.*, 2001; Pilz-Burstein *et al.*, 2010; Bonitch-Dominguez, Bonitch-Gongora, Padial & Feriche, 2011). The diminished plasma lactate response in the current study may reflect a change in the activity of the competitors and/or metabolic function as the combats progressed (Ballor & Volovsek, 1992; Gaitanos *et al.*, 1993; Baudry & Roux, 2009). The reduced plasma lactate response in concert with increased HR responses in the final combat is consistent with the responses of a number of investigations demonstrating an increased shift towards aerobic metabolism and diminished anaerobic energy yield during repeated intense intermittent exercise (Gaitanos *et al.*, 1993; Bogdanis *et al.*, 1996; Dorado *et al.*, 2004; Glaister, Stone, Stewart, Hughes & Moir, 2005). As intense intermittent exercise is repeated, glycolysis is often inhibited resulting in an increased reliance on aerobic metabolism and PCr to fuel contractile activity (Gaitanos *et al.*, 1993; Bogdanis *et al.*, 1996). The reduced glycolytic activity in these exercise settings is thought to be mediated by changes in the metabolic environment (e.g. reduced pH, and increased H^+ and cytosolic citrate) that inhibit the main glycolytic regulatory enzymes phosphorylase and phosphofructokinase (Gaitanos *et al.*, 1993; Bogdanis *et al.*, 1996). Muscle glycogen availability may also play a role, but this would be dependent on the magnitude of the glycogen depletion during the activity (Bangsbo, Graham, Kiens & Saltin, 1992; Langfort *et al.*, 1997; Balsom, Gaitanos, Soderlund & Ekblom, 1999; Iaia, Perez-Gomez, Nordsborg & Bangsbo, 2010). During high intensity intermittent exercise, increased plasma NEFA availability may also diminish the rate of glycolysis via citrate-mediated inhibition of phosphofructokinase (Langfort *et al.*, 1997; Odland, Heigenhauser, Wong, Hollidge-Horvat & Spriet, 1998). Although the current study design precludes the precise quantification of such mechanisms, these HR and plasma lactate responses corroborate the responses of a number investigations demonstrating a progressive shift towards aerobic metabolism and reduced glycolytic activity as intense intermittent exercise is repeated

(Gaitanos *et al.*, 1993; Bogdanis *et al.*, 1996; Dorado *et al.*, 2004; Glaister *et al.*, 2005). More invasive measurement techniques (e.g. muscle biopsy and gas exchange measures) are necessary to confirm these responses in future.

The significant rise in plasma glucose between the pre and post sampling periods was greater in magnitude in combats 1 and 4 compared with combat 3, and a significant rise in glucose was absent from combat 2. It appears then, that the hepatic glucose outpouring into the circulation during each combat was sufficient to generate a rise in glycaemia, but this response was temporally diminished in the second combat (Marliss *et al.*, 2000). This finding corroborates earlier research demonstrating reduced hyperglycaemic and hyperinsulinemic responses when a second bout of intense exercise is repeated within 1 hour (Marliss *et al.*, 1991). The reduced glucose responses in this investigation were a function of increased glucose utilisation and enhanced glucose clearance during the second exercise bout (Marliss *et al.*, 1991). Similar mechanisms may be responsible for the reduced glucose responses to the second combat in the present investigation, but further measures would be needed to quantify this proposition. It is difficult to explicate the partially restored glucose response in the final combat, but this could represent some form of altered glucoregulation.

A number of investigators have identified an important role for lipid oxidation during repeated bouts of high intensity intermittent exercise (Balsom, Gaitanos, Soderlund & Ekblom, 1999; Trapp, Chisholm & Boutcher, 2007). In support of this idea, plasma glycerol increased significantly between the pre and post sampling periods in each of the four Taekwondo combats, though plasma NEFA remained unaltered. This response is consistent with the glycerol and NEFA responses reported during intense exercise and suggests that each Taekwondo combat promoted increased lipolytic activity (Romijn *et al.*, 1993; Horowitz & Klein, 2000). Research frequently demonstrates enhanced rates of exercise-induced lipolysis during the second exercise bout when the same exercise is repeated within 20 to 60 minutes (Stich *et al.*, 2000; Goto *et al.*, 2007). While significantly higher plasma glycerol and NEFA concentrations were measured in combat 3 compared with both combat 1 and combat 2, the actual glycerol and NEFA responses (e.g. increase between the pre and post sampling periods) remained unaltered between each of the successive combats. The higher glycerol and NEFA concentrations measured in the third combat seem to represent continued release of these metabolites into the circulation during the rest interval (Romijn *et al.*, 1993; Mulla *et al.*, 2000) as opposed to enhanced lipolytic activity as a function of the activity of the third combat (Stich *et al.*, 2000; Goto *et al.*, 2007). This notion is further support by the reduced NEFA and glycerol concentrations measured in combat 4 following a more lengthy 156 minute rest interval.

A significant rise in plasma noradrenaline was evident between the pre and post sampling periods in each of the four combats, but plasma adrenaline remained unchanged. The absence of a significant increase in plasma adrenaline between the pre and post sampling periods seems to be a consequence of the extremely high baseline concentrations preceding each combat. This may reflect a more pronounced anticipatory rise of plasma adrenaline prior to combat and supports the earlier notion of elevated stress responses in the moments preceding combat (Chapter 4.2) (Richter *et al.*, 1996; Filaire, Sagnol, Ferrand, Maso & Lac, 2001; Gerra *et al.*, 2001; Goldstein & Kopin, 2008). These incongruent hormonal profiles are consistent with the notion that adrenaline secretion from the chromaffin cells of the adrenal medulla is not regulated in parallel with noradrenaline released by the sympathetic nerve endings (Shah, Tse, Clutter & Cryer, 1984; Eisenhofer *et al.*, 1995; Greiwe, Hickner, Shah, Cryer & Holloszy, 1999). Indeed, adrenaline functions as a hormone and is released directly into the bloodstream to act at cells distant from the adrenal gland. This contrasts the noradrenaline released from the sympathetic nerve endings, which as a neurotransmitter act close to the sites of release and are then removed back into the neurons by neuronal reuptake (Eisenhofer *et al.*, 1995; Goldstein *et al.*, 2003).

A disparity in the plasma adrenaline and noradrenaline responses was also evident across the successive combats. The rise in plasma noradrenaline was attenuated after the first combat and this diminished response was maintained throughout the remainder of the repeated combats. In contrast, no differences in the plasma adrenaline responses were observed between the repeated combats. A small, but significant, reduction in the overall adrenaline concentration was, however, temporally observed in combat 3 compared with combat 2. A trend for reduced plasma catecholamine responses has also been identified while performing repeated Wrestling combats (Kraemer *et al.*, 2001; Barbas *et al.*, 2010). Interestingly, though, this phenomenon has seldom been observed in other exercise settings and this contrasts the increased and/or unaltered endocrine response typically encountered during repeated bouts of endurance exercise (Stich *et al.*, 2000; Ronsen, Haug, Pedersen & Bahr, 2001; Ronsen, Kjeldsen-Kragh, Haug, Bahr & Pedersen, 2002).

While the synergistic actions of catecholamines and allosteric regulators may modulate metabolic function during repeated Taekwondo combats (Chapter 4.2), the ability to secrete plasma catecholamines is important for repeated intense short-term exercise performance (Kraemer *et al.*, 2001; Zouhal *et al.*, 2001; Zouhal *et al.*, 2008). Indeed, diminished plasma catecholamine responses have been implicated in the reduced physical performances that are experienced during repeated Wrestling combats (Kraemer *et al.*, 2001). Given the importance of plasma catecholamines in this context, it seems necessary to detail the precise factors that regulate the diminished catecholamine response in this form of exercise. Unfortunately, however, the exact mechanistic basis of the diminished catecholamine responses in this exercise setting remains elusive. An accumulation of fatigue, dehydration and the inability to re-synthesise catecholamines in the chromaffin cells of the adrenal medulla were initially proposed to explicate this occurrence during repeated Wrestling combats (Kraemer *et al.*, 2001).

Although a number of prospective theories have been formulated, there is some evidence to implicate altered rates of catecholamine synthesis, release and metabolism in the diminished catecholamine responses during this form of repeated intense intermittent exercise (Kraemer *et al.*, 2001; Bracken, Linnane & Brooks, 2009). The attenuation in plasma adrenaline and noradrenaline concentrations during repeated Wrestling combats, for instance, were accompanied by marked increases in plasma dopamine (Kraemer *et al.*, 2001). Dopamine plays an important role in modulating SAM activity by increasing catecholamine synthesis in the sympathetic nerves and the adrenal medulla chromaffin cells, as well as through increased peripheral dopaminergic activity (Smit, Lieverse, van Veldhuisen & Girbes, 1995; Eisenhofer, Huynh, Hiroi & Pacak, 2001). More precisely, dopamine formed from 3,4-dihydroxyphenyl-alanine (DOPA) in the presence of the enzyme L-aromatic amino acid decarboxylase (L-AADC), is typically converted to noradrenaline by dopamine-β-hydroxylase (Ahn & Klinman, 1989; Eisenhofer *et al.*, 2001). The additional actions of phenylethanolamine N-methyltransferase (PNMT), mainly localised to the chromaffin cells of the medulla, leads to the conversion of noradrenaline to adrenaline (Eisenhofer *et al.*, 2001). The stimulation of D_2 dopamine receptors by increased dopamine concentrations also inhibit noradrenaline release during sympathetic activation (Smit *et al.*, 1995). The increased plasma dopamine in concert to diminished plasma noradrenaline during repeated combats may therefore reflect the combined actions of reduced dopamine-β-hydroxylase conversion of dopamine to noradrenaline, increased dopamine spillover into the circulation and enhanced dopamine-mediated activation of D_2 receptors (Mannelli *et al.*, 1995; Stanley *et al.*, 1997; Murphy, 2000; Kraemer *et al.*, 2001).

It seems worthy to note at this stage that research investigating the catecholamine responses to repeated intense intermittent exercise is not extensive. The most recent evidence demonstrates that repeated intermittent sprint exercises also induce marked increases in plasma nephrines, normetanephrine (NMET) and metanephrine (MET) (Bracken *et al.*, 2009). This finding suggests an increased rate of noradrenaline and adrenaline metabolism via catechol-O-methyltransferase (COMT) outside of the sympathetic neuron during this form of repeated intense intermittent exercise (Eisenhofer *et al.*, 2001). The similarities in the repeated intense intermittent activity profiles, and the physiological and hormonal responses between these generic and combat-sport exercise settings (Kraemer *et al.*, 2001; Bracken *et al.*, 2009) raise the distinct possibility that enhanced catecholamine metabolism in concert to reduced rates of catecholamine synthesis and release may play integral a role in mediating the diminished catecholamine responses in these repeated combat-sport settings. Further research is, however, required to elucidate the precise mechanistic basis of this response. This information may be valuable to inform the development of interventions to minimise attenuations in competitors' physical performance capabilities during a championship event.

5.1.5 Conclusions and Practical Applications

The primary findings of this study demonstrate that performing repeated Taekwondo combats in an ecologically valid competition time structure modulates the physiological and hormonal responses to combat and perturbs homeostasis between the combats. Most notably, the successive combats resulted in reduced plasma noradrenaline and lactate responses to combat and increased HR responses earlier in combat. These responses may reflect a change in the activity of the competitors' and/or altered metabolic function in favour of an increased reliance on aerobic metabolism and diminished anaerobic energy yield as the combats are repeated. More invasive measurement techniques would, however, be necessary to confirm such metabolic adjustments. Importantly, the HR and plasma concentrations of glycerol, NEFA and lactate remained elevated above baseline levels between a number of the repeated combats. This suggests that the recovery processes were often incomplete between the combats. These findings emphasise the importance of adopting strategies to facilitate the recovery process and enhance energy availability between repeated combats in championship events.

CHAPTER 6

SYNTHESIS OF FINDINGS

SYNTHESIS OF FINDINGS

The aim of this chapter is to interpret and integrate the findings contained within the thesis. Realisation of the aims and objectives will be initially addressed in this section. The general discussion that follows will attempt to contextualise the training applications and methodological implications of the study findings. The limitations of the data and recommendations for future research are also considered in this section.

6.1 REALISATION OF AIMS AND OBJECTIVES

The aim of this investigation was to examine the physiological demands of competitive Taekwondo. This was achieved through the fulfilment of the research objectives devised in Chapter 1. The physiological responses to Taekwondo competition and training (Objective 1), and the activity profiles in Taekwondo competition (Objective 2) were initially examined to provide a fundamental ergonomic evaluation of the sport. The data obtained from the successful fulfilment of these objectives provided the ergonomic framework required to devise a simulation of Taekwondo competition (Objective 3). These Taekwondo simulations (Objective 3) were subsequently implemented to provide a more detailed examination of the physiological demands of Taekwondo competition (Objective 4).

6.2 GENERAL DISCUSSION

The aim of this section is to interpret and integrate the findings contained within the thesis. The discussion will attempt to contextualise the training applications and methodological implications of the study findings. It is hoped that the systematic appraisal of these themes will result in the development of two distinct frameworks to guide the training process in Taekwondo and to inform future research into the demands of this combat sport.

6.2.1 Training Applications

The findings contained within the studies of this thesis contribute original information to the understanding of the physiological demands of competitive Taekwondo. These findings may, therefore, be integrated into an ergonomics model of the Taekwondo training process (Figure 6.2.1). An ergonomics model allows training to be considered as interfacing with the specific demands of competition and the physical capabilities of the competitors (Reilly, 2005). The activity pattern of Taekwondo combat imposes high aerobic and anaerobic physiological demands on the competitors (Chapters 3.1, 3.2, 4.1 & 5.1) who must possess the necessary physical capabilities to cope with these requirements. This contrasts the longstanding view of a number of coaches and researchers who suggest that aerobic metabolism is of minor importance for Taekwondo competition (Heller *et al.*, 1998). Indeed, the structure of conventional training practices seem to be largely directed towards the development of competitors anaerobic performance abilities with less emphasis on developing aerobic adaptations for competition (Chapter 3.3). While anaerobic metabolism may be important to fuel the high intensity efforts (Chapters 3.1 & 3.2), coaches and practitioners should be aware that aerobic metabolism makes a significant contribution to the activity of combat (possibly to fuel the lower intensity actions and the recovery processes between the intense efforts), and this becomes more prominent as the competitors' engage in repeated combats to reach their final match (Chapter 5.1). Coaches and practitioners may, therefore, be advised to consider restructuring conditioning practices and sessions to prepare competitors for the high aerobic and anaerobic requirements of competition. These training sessions may include a range of generic and Taekwondo-specific activities depending on the objectives of the session and the specific phase of training within a periodised training programme (e.g. general/specific preparatory phase or competition phase) (Pieter & Heijmans, 2003; Bompa & Haff, 2009).

An understanding of the physiological demands of training is required to inform the structure of conditioning sessions for competition (Reilly, 2005). The information contained in this thesis demonstrates that different Taekwondo training activities mediate diverse cardiovascular requirements (Chapter 3.3). Moderate relative cardiovascular intensities are elicited by the practice of elastics, step sparring, and technical combinations. These cardiovascular intensities suggest that such activities may be better suited to developing functional strength, power and correct technique as opposed to cardio-respiratory adaptations. The practice of technical combinations with pads for additional resistance increases the cardiovascular responses to this technical practice. Coaches may, therefore, consider using pads during these technical practices to increase cardio-respiratory adaptations if necessary (Helgerud *et al.*, 2007). The practice of forms, basic techniques and forms practiced interchangeably, sparring drills, and free sparring elicit the greatest cardiovascular demands. These practices would presumably incite more pronounced cardio-respiratory adaptations than Taekwondo activities that elicit moderate cardiovascular intensities (Helgerud *et al.*, 2007). Practically, this information is valuable to assist coaches in the selection of specific activities in accordance with the training session objectives. Unfortunately, however, the intensities of conventional Taekwondo training activities and sessions, delivered by experienced international coaches, are often insufficient to prepare competitors for the cardiovascular demands of international Taekwondo competition (Chapters 3.1 & 3.3). This may be a function of the inappropriateness of training to emulate the physical activity requirements of combat and/or the failure of training to incite the stress responses that are experienced in championship events (Chapter 4.2). Coaches may, therefore, need to reconsider the structure of Taekwondo practices to ensure that the stimulus is suitable to prepare competitors for the physical activity requirements and the stress responses that are experienced in championship combats.

The activity profile information contained within this thesis (Chapter 3.2) provides a valuable ergonomic framework to prepare competitors for the physical activity requirements (activity pattern) of championship Taekwondo combat. Conditioning sessions that incorporate similar activity phase sequences, activities, number of actions and fighting to non-fighting activity intervals to those performed in championship combats may provide a suitable stimulus for this purpose. This approach to training should promote specific structural adaptations to optimise physiological function and performance in Taekwondo combat (Campos *et al.*, 2002; Reilly *et al.,* 2009). The regular monitoring of ‘field-based’ physiological indices, such as HR and blood lactate, may be valuable to ensure that the activity patterns of such training practices elicit suitable intensities to promote such adaptations. This may be achieved with the assistance of a physiologist and the use of modern-day continuous and telemetry HR monitor systems, and portable lactate monitors. Coaches and practitioners might be advised to ensure that competition-specific conditioning activities, such as sparring drills and free sparring, elicit similar HR intensities (e.g. %HRmax and the time spent in specific HR training zones) and blood lactate concentrations as those observed in championship competition (Chapter 3.1 & 4.2). These intensities and activities should be suitable to prepare competitors for the specific aerobic and anaerobic requirements of combat (Pilegaard *et al.*, 1999; Helgerud *et al.*, 2007).

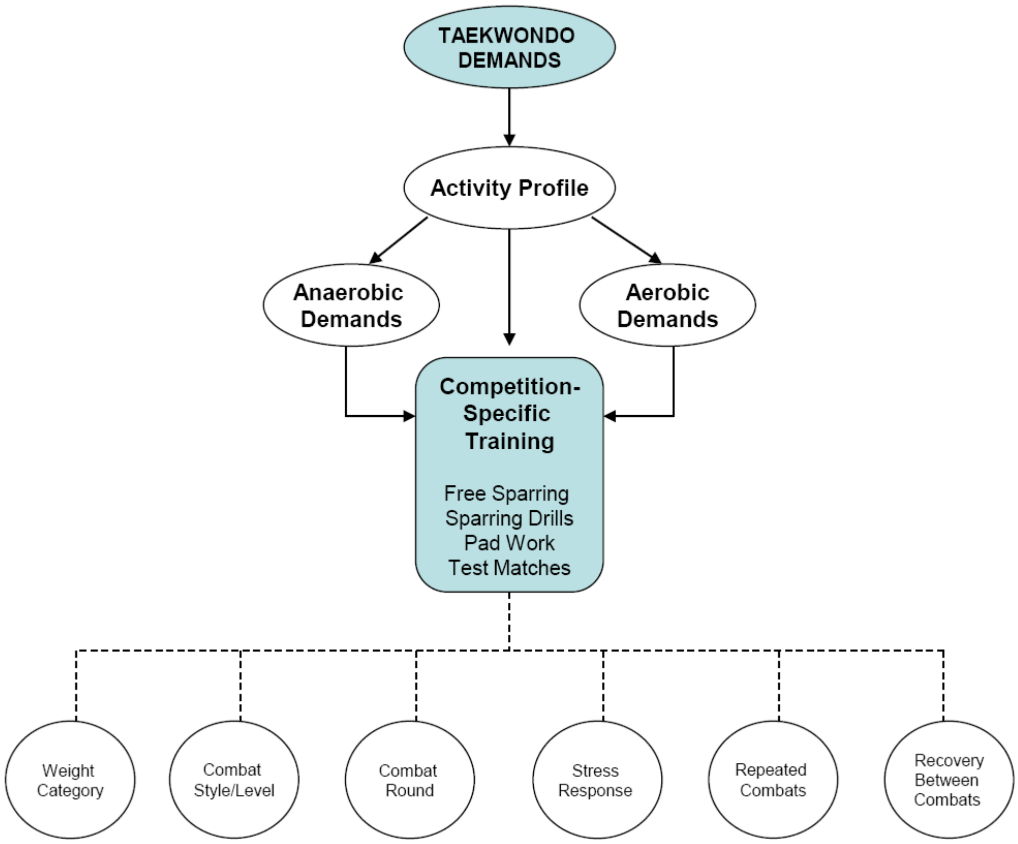
The activity profile information contained within the thesis also permits the opportunity to specialise conditioning sessions to the requirements of a number of situational factors. Firstly, conditioning sessions may need to prepare competitors for the increased activity levels and physiological demands that occur across the rounds of combat (Chapters 3.1, 3.2 & 4.1). These specific activity adjustments may also be considered to manipulate the intensities of pad work, sparring drills, and free sparring practices to prepare competitors for the demands of combat and to satisfy the requirements of different training objectives within particular training phases (Bouhlel *et al.*, 2006; Baudry & Roux, 2009). The activity profile information also suggest that competition-specific conditioning sessions should be specialised to the activity requirements of specific weight categories (Chapter 3.2). Most notably, heavy weights are subjected to greater fighting demands, whereas feather weights engage in longer preparatory periods and less frequent fighting exchanges (Chapter 3.2). Coaches and practitioners may, therefore, wish to accommodate for these specific activity requirements in both specific and generic training practices. These incongruent activity profiles may also have implications for the selection of sparring partners for sparring drills and free sparring in training. Differences in the activity patterns between the WTF international level Taekwondo combats in this thesis (Chapter 3.2) and ITF and STF structured national level combats in previous research (Heller *et al.*, 1998; Matsushigue *et al.*, 2009) suggest that this information may have limited value for preparing competitors for other combat styles and/or levels of competition. Taekwondo conditioning sessions may, therefore, need to be configured to the requirements of the specific level of competition and/or style of combat, which requires further research evidence (Chapter 3.2).

In addition to preparing competitors for the specific physical requirements (activity profile) of Taekwondo combat, coaches may also need to consider approaches to assist competitors' to effectively manage the stress responses associated with fighting in championship events (Chapters 3.3 & 4.2). As the physical workload of the combat activity and the stress response to fighting may play an integral role in regulating metabolic function in championship combats (Chapter 4.2), a psychophysiological approach to conditioning may be necessary. This may include the use of 'psychological skills training' to alleviate competition state anxiety and the negative emotions associated with the stress response (Chapman *et al.*, 1997; Pieter & Heijmans, 2000), and/or the systematic exposure (short periods of habituation) of the competitors to the physical activity and the stress responses of fighting (Grissom & Bhatnagar, 2009). A Taekwondo 'test match' structure may serve as a suitable 'psychophysical' training framework for the latter concept (Chapter 5.1), but the injury risk associated with this practice is high. While both of these training approaches may be valuable to assist competitors to more effectively manage the stress hormonal responses in combat (Perna, Antoni, Kumar, Cruess & Schneiderman, 1998; Gerra *et al.*, 2001; Grissom & Bhatnagar, 2009), further research into the efficacy and safety of these approaches in Taekwondo is advised before such techniques can be effectively implemented into training programmes.

The physiological and hormonal responses to performing successive combats in this thesis also provide an important framework to inform competition preparations and the selection of interventions during a championship event. An important finding of this investigation was that the recovery processes were largely incomplete when short recovery intervals occurred between the repeated combats (e.g. 31 minutes). It may, therefore, be important to consider strategies to facilitate the recovery processes between the combats and/or optimise physiological function during each combat (e.g. reduce acidosis and the cardiovascular strain). A range of strategies may be valuable to optimise physiological function during combat. These include the development of specialised conditioning sessions to more effectively prepare competitors for the aerobic and anaerobic physical requirements of the activity (Chapters 3.1 & 3.2), strategies to effectively manage the stress responses to fighting in championship events (Chapter 4.2), and the use of nutritional interventions to facilitate energy availability and attenuate metabolite accumulation (e.g. creatine, sodium bicarbonate, beta-alanine and carbohydrate supplementation/availability) (Glaister, 2005; Derave, Everaert, Beeckman & Baguet, 2010). Such strategies may have the potential to reduce the recovery requirements of each combat (Borsheim & Bahr, 2003) and to some extent mitigate the diminished noradrenaline release and possible reduction in anaerobic energy yield associated with performing repeated combats (Chapter 5.1). In situations where short recovery periods between the combats are anticipated (e.g. ~ 30 minutes), it may be valuable to consider implementing strategies to facilitate the recovery processes. The use of light intensity exercise (active recovery), for instance, has been shown to facilitate the removal of blood and muscle metabolites such as lactate and pH following intensive exercise (Sairyo, Ikata, Takai & Iwanaga, 1993; Franchini *et al.*, 2009). In this section, attempts have been made to contextualise the practical applications of this framework and outline strategies that may be advantageous for competition preparations. Further research is, however, necessary to determine the effectiveness of such strategies in optimising physiological function and performance in Taekwondo.

In summary, Taekwondo competition imposes a range of demands on the competitors who must possess the necessary psychophysical capabilities to cope with these requirements. An ergonomics model of Taekwondo training is, therefore, proposed to guide the training process for the specific requirements of championship competition (Figure 6.2.1). Conditioning sessions should attempt to prepare competitors for the specific physical activity requirements (activity profile) of championship combats (Chapter 3.2). Taekwondo practices such as pad work, sparring drills, free sparring and test match events may be most suitable for this purpose (Chapter 3.3). These activity practices should sufficiently stimulate both aerobic and anaerobic metabolism (Chapters 3.1 & 4.2), and they should consider the specialised activity requirements of different weight categories, the style/level competition and the changes in activity performed across the rounds (Chapter 3.2). Conditioning should also consider preparing the competitors' to manage the stress responses associated with fighting in championship events (Chapter 4.2) and the demands of performing repeated combats with different recovery intervals (Chapter 5.1) (Figure 6.2.1). Training that is structured according to the principles of this ergonomics model should serve to promote specific structural adaptations to optimise physiological function and performance in this combat sport.

Figure 6.2.1: Ergonomics model of Taekwondo training



6.2.2 Specific Training Recommendations

The previous section has made efforts to integrate the findings of the thesis into an ergonomics model to guide the training process for the specific demands of Taekwondo competition. This section will attempt to further contextualise the practical applications of the findings by proposing specific training strategies that may assist coaches to more effectively prepare competitors' for the requirements of championship events.

Competition-Specific Conditioning Strategies to Prepare Competitors' for the Physical Activity and the Physiological Demands of Combat

The investigation into the physiological demands of conventional Taekwondo training in Chapter 3.3 demonstrates that the training stimulus (e.g. the intensity, duration and frequency of the activity practices) may have been insufficient to prepare competitors' for the demands of championship events. As such, coaches are advised to reconsider the structure of competition-specific conditioning practices and sessions to ensure that the stimulus is suitable to prepare the competitors' for the demands of competition. In the 'specific preparatory' and 'competition' phases of a Taekwondo periodised plan, sparring-based activities such as free sparring and sparring drills, and pad work should be used to promote specific structural and functional adaptations for competition (Chapter 3.3). These should be performed using high-intensity intermittent exercise bouts that closely replicate the format of combat (e.g. three two-minute rounds with one-minute rest intervals). The available data on the activity profiles of championship combats in Chapter 3.2 provide the fundamental framework required to structure these sessions. Sparring-based activities and pad work should include regular high-intensity fighting actions lasting between 1 and 6 s and these should be interspersed with varied non-fighting activity periods (e.g. preparatory, non-preparatory and stoppage activity phases) ranging between 1 and 16 s. In keeping with the championship data, the vast majority of the fighting actions during these practices should last between 1 and 2 s and these should be interspersed with sporadic fighting periods that are longer in duration, typically between 2 and 6 s (Chapter 3.2). The competitors' should aim to perform between 8 and 11 fighting exchanges and between 8 and 13 kicks during each round of the training combats (Chapter 3.2). In competition, most of the non-fighting periods (70%) last less than 16 s, with half (50%) lasting less than 10 s, and a substantial proportion (32%) spanning $\leq$ 6 s. Coaches should consider these proportions when varying the non-fighting periods of these conditioning sessions. The different combinations of fighting and non-fighting periods used in training should mimic the average fighting to non-fighting ratios performed in championship combats (e.g. average fighting to non-fighting ratio of 1:6). A mean cadence of ~ 1.7 s of fighting activity interspersed with 6.4 s of preparatory activity and 3 s of non-preparatory activity may serve as a generic template to achieve this fighting to non-fighting activity ratio.

The intensities of these sparring practices and pad work should attempt to recreate the aerobic and anaerobic demands of competition. To promote specific cardio-respiratory adaptations for competition, the activity performed in each round of the sparring and pad work bouts should elicit mean HR's $\geq$ 90% of competitors HRmax (competition range: 90 to 97%) (Chapters 3.1, 4.2 & 5.1). The proportion of time spent in 'hard' (70 to 89% HRmax) 'very hard' (90 to 99% HRmax) and 'maximum' (100% HRmax) HR intensity zones during the sparring and pad work bouts should also attempt to recreate those in competition. In this regard, competitors' should spend the largest proportion of time in 'very hard' (90 to 99% HRmax) HR intensity zones during sparring and pad work practices (Chapter 3.1). It may also be important to ensure that the competitors' spend some time at 'maximal' intensity during such practices. Coincidentally, generic exercise training performed between 90 and 95% of HRmax promotes the most pronounced increases in individuals $\dot{V}O_{2max}$ (Helgerud *et al*., 2007). As such, these recommended Taekwondo training intensities may not only be suitable to prepare competitors' for the specific cardio-respiratory demands of combat, but it may also promote marked increases in the competitors' $\dot{V}O_{2max}$. To further ensure specificity of the adaptations for competition, these sessions may also consider replicating the increased cardiovascular demands that occur across the rounds of combat (Chapters 3.1, 4.1 and 5.1). During the sparring and pad work practices, coaches should aim to achieve mean target HR's of 90, 93 and 96% of HRmax for rounds (bouts) 1, 2, and 3, respectively. In line with the championship combats, these practices should attempt to elicit progressive increases in the time spent in 'very hard' (90 to 99% HRmax) HR intensity zones and reduced time in 'hard' (70 to 89% HRmax) HR intensity zones across the rounds. This may be achieved by increasing the activity levels across the rounds of the exercise bouts in a similar fashion to championship combat (Chapter 3.2). In this regard, the competitors' should attempt to perform a greater number of exchanges and kicks, and less preparatory activity as the rounds of such practices progress. These activity changes should reduce the fighting to non-fighting ratios across the rounds (e.g. target fighting to non-fighting ratios of 1:8 and 1:5 for rounds 1 and 3, respectively).

Consideration of the frequency and the duration of these activity practices is also important to elicit cardio-respiratory adaptations for competition. The recommended guidelines for improving and maintaining cardio-respiratory fitness are intensities of training between 65 and 90% of HRmax, performed for a minimum of 20 minutes per session (or a number of 10-minute bouts throughout the day), 3 to 5 times per week (ACSM, 1998). Recent research demonstrates that performing 16 minutes of high-intensity interval training (90 to 95% HRmax) 3 times per week is also suitable to elicit significant gains $\dot{V}O_{2max}$ (Helgerud *et al*., 2007). A range of diverse high-intensity intermittent exercise protocols may be utilised to enhance $\dot{V}O_{2max}$. For example, both short 15:15 s exercise:rest intervals (e.g. 47 repetitions of 15 s intervals at 90 to 95% HRmax interspersed with 15 s rest) and longer 4:3 minute exercise:rest intervals (e.g. 4 repetitions of 4-minute intervals at 90 to 95% HRmax interspersed with 3 minutes rest) are equally effective in increasing $\dot{V}O_{2max}$ (Helgerud *et al*., 2007). In fact, these intermittent exercise strategies are more effective in enhancing $\dot{V}O_{2max}$ than training continuously at lactate threshold (85% HRmax) or using long slow distance running (70% HRmax). As such, the sparring and pad work practices used to prepare Taekwondo competitors' for the cardio-respiratory demands of competition should be structured using repeated high-intensity intermittent exercise bouts. These exercise bouts should be performed at least 3 times per week for a minimum of 16 minutes per session.

Performing repeated high-intensity intermittent sparring and pad work exercises in a structure that is representative of championship combat (e.g. three two-minute rounds interspersed with one-minute rest intervals) may be suitable to achieve the minimum recommended duration of 16 minutes per session. More specifically, performing three to four sets of sparring or pad work exercise (e.g. each set constitutes three two-minute rounds with one-minute rest intervals) interspersed with longer recovery intervals (e.g. 5 to 15 minutes) would satisfy the minimum duration recommended for improving and maintaining cardio-respiratory fitness (ACSM, 1998). This format may be particularly suited to shorter training sessions lasting between 1 and 2 hours. Alternatively, sets of sparring and pad work exercise may be performed in both the AM and PM sessions across a single day. For example, coaches could schedule three sets of sparring or pad work in the AM session (9:00 to 11:00) and a further three sets in the PM session (3:00 to 5:00). This would conform to the ACSM'S recommendations, which suggest that a number of exercise bouts may be performed throughout the day as opposed to using a single 20-minute session (ACSM, 1998). This format may be particularly useful in instances where the coach wishes to replicate the recovery intervals that occur between the combats in championship events (e.g. test-match structure) (Chapter 5.1). As these sparring and pad work exercises may be extremely demanding upon both aerobic and anaerobic metabolism, coaches should ensure suitable recovery between such sessions. A minimum of 36 to 48 hours is recommended between these intensive conditioning sessions (depending on the overall training load) (Helgerud *et al*., 2007). Dramatic improvements in the competitors' competition-specific cardio-respiratory fitness may be achieved within 12 weeks of initiating such high-intensity interval training (Helgerud *et al*., 2007).

The intensities of these sparring and pad work practices should also be suitable to promote anaerobic adaptations for competition. The activity patterns recommended to elicit cardio-respiratory adaptations earlier in this chapter may also be suitable to elicit anaerobic adaptations for competition (Chapter 3.2). As such, the blood lactate responses to these sparring and pad work practices should attempt to replicate those measured in championship combats. In line with the championship combats, the high-intensity sparring and pad work exercises should attempt to elicit high post exercise blood lactate concentrations (e.g. $\geq$ 10 mmol.l^{-1}) (Chapter 3.1). Regular training that elicits high lactate concentrations results in significant improvements in glycolytic capacity and muscle MCT1 and MCT4 lactate and H^+ transport capacity (often referred to as 'lactate tolerance training') (Juel *et al*., 2004; Burgomaster *et al*., 2007; Mohr *et al*., 2007; Pilegaard *et al*., 2009). Consideration of the duration and the frequency of these training practices is also important for developing the competitors' lactate and H^+ transport capacity. In the literature, enhanced MCT1 and MCT4 lactate and H^+ transport capacity has been developed by performing 2 to 20 minutes of high intensity exercise 3 to 5 times per week (Juel *et al*., 2004; Burgomaster *et al*., 2007; Mohr *et al*., 2007; Pilegaard *et al*., 2009). As such, these durations and frequencies may be used to guide the structure of 'lactate tolerance sessions' in Taekwondo. Especially since there are no official recommendations available to inform the structure of such conditioning practices. As there are similarities in the exercise durations and frequencies needed to evoke both aerobic and anaerobic adaptations, these may be trained simultaneously using an identical structure to that proposed for cardio-respiratory conditioning. That is, three to four sets of sparring or pad work exercise (e.g. each set comprising three two-minute rounds with one-minute rest intervals) interspersed with longer recovery intervals (e.g. 5 to 15 minutes). These sessions should be performed 3 to 5 times per week. Significant improvements in lactate and H^+ transport capacity may be expected within 1 to 8 weeks of initiating such training sessions (Juel *et al*., 2004; Burgomaster *et al*., 2007; Mohr *et al*., 2007; Pilegaard *et al*., 2009).

A number of Taekwondo coaches often implement additional pad work sessions into training, which are devoted solely to developing competitors' 'lactate tolerance' capabilities. In the literature, high-intensity exercise bouts lasting between 6 and 60 s interspersed with 1 and 4 minute rest intervals have been used to elicit high lactate concentrations for developing lactate and H^+ transport capacity (Juel *et al*., 2004; Burgomaster *et al*., 2007; Mohr *et al*., 2007; Pilegaard *et al*., 2009). This information may serve as valuable framework to guide the structure of 'lactate tolerance training' in Taekwondo, but these exercise durations are not specific to the activity patterns performed in combat (Chapter 3.2). To enhance the specificity of 'lactate tolerance training' for Taekwondo, the fighting and non-fighting durations performed in championship combats could be used as a template. For example, the use of repetitive fighting activities lasting 1 to 6 s interspersed with 1 to 16 s of non-fighting activity in various combinations are recommended. Various combinations of these actions that elicit high lactate concentrations should, in theory, be suitable to promote increased lactate and H^+ transport capacity (Mohr *et al.*, 2007). Regular monitoring of blood lactate concentrations is, therefore, important during these sessions.

Specialising Competition-Specific Conditioning for Different Weight Categories

The previous section has proposed specific training strategies that may assist coaches to more effectively prepare Taekwondo competitors' for the fundamental physiological requirements of championship events. The activity profile information contained in Chapter 3.2 also offers coaches the opportunity to specialise conditioning practices to the activity requirements of specific weight categories (e.g. fin, feather and heavy weight competitors). The data contained in Chapter 3.2 demonstrate a predominance of fighting activity for heavy weights, and preparatory activity and less frequent fighting exchanges for feather weights during championship combats. As such, coaches are advised to accommodate for such variation in both sparring and pad work practices to ensure specificity of the physiological adaptations for competition.

During sparring and pad work exercises (structured across three two-minute rounds with one-minute rest intervals), heavy weights should perform fighting actions for longer periods than fin weights. To achieve this, heavy weights should perform more frequent 'prohibited acts' during each exchange as opposed to executing an increased number of kicks and/or exchanges (Chapter 3.2). These actions should include holding, pushing and/or body to body contact against an opponent using both concentric and isometric contractions of the upper and lower body musculature. During each fighting exchange in both sparring and pad work exercises, these actions may be performed before, during and/or after executing other fighting actions (e.g. kicks). This would replicate the variation apparent in championship combats. In agreement with the championship combat data, these prohibited acts may be performed for 1 to 4 s during each exchange, but the vast majority of such actions should last < 2 s. During heavy weights sparring and pad work practices, coaches should ensure that a minimum of two-thirds (2/3) of all fighting exchanges include prohibited acts alongside other fighting actions. In fact, the large variation in the number of prohibited acts performed in the championship combats (Chapter 3.2) would suggest that some heavy weight competitors may need to perform these actions on a more frequent basis (e.g. 5 out of every 6 fighting exchanges should include prohibited acts). This strategy should be suitable to prepare heavy weight competitors' for the additional energy demands imposed by these activities during combat. In contrast, less frequent prohibited acts are recommended for fin and feather weights' sparring and pad work practices. Prohibited acts should be performed in one-third (1/3) and one-half (1/2) of all fighting exchanges in fin and feather weights sparring and pad work exercises, respectively. The increased frequency of prohibited acts performed by heavy weights in the championship combats results in an approximately two-fold increase in the number of general stoppages performed after each exchange (Chapter 3.2). Coaches are therefore advised to incorporate a greater number of stoppages into heavy weights sparring and pad work practices. To this end, coaches should consider implementing one 3 s stoppage after every 2-3 fighting exchanges in heavy weights sparring and pad work practices. In contrast, one 3 s stoppage after every 5-6 fighting exchanges is advised for fin and feather weights sparring and pad work practices.

The quantity of preparatory and non-preparatory activity performed within sparring and pad work exercise should also be specialised to the requirements of these specific weight divisions. During such practices, feather weights should perform preparatory activity for longer periods (on average ~ 8 s) than their fin (~ 5 s) and heavy (~ 6 s) weight counterparts' prior to executing each fighting exchange. Coaches should include combinations of different preparatory activity periods (e.g. 1 to 16 s) within sparring and pad work practices to satisfy these preparatory activity recommendations. To achieve longer preparatory periods, feather weights should (on average) perform less frequent fighting exchanges (n = 24) than fin (n = 29) and heavy weights (n = 32) during these practices (e.g. during sets structured across three two-minute rounds with one-minute rest intervals). In agreement with championship combats, feather weights should also execute a greater number of kicks per exchange (e.g. use more kicking combinations) during such practices. Feather weights should also engage in less regular active recovery movements (non-preparatory activity) than fin and heavy weights after each exchange to promote longer preparatory activity periods (Chapter 3.2). In this regard, less than half (45%) of the fighting exchanges performed by feather weights during sparring and pad work should be followed by active recovery movements lasting 3 s (Chapter 3.2). For the remainder of this time, feather weights should re-engage directly with preparatory activity. This strategy should prepare feather weights for the sustained preparatory activity and infrequent active recovery movements imposed by championship combats. In contrast, fin weights should perform 3 s of active recovery movement after every fighting exchange and heavy weights after two-thirds of all fighting exchanges.

Competition-Specific Training Strategies to Manage the Stress Response

The previous sections provide detailed recommendations to assist coaches to prepare the competitors' for the specific physical (activity profile) and physiological requirements of Taekwondo combat. In addition to preparing competitors' for the physical requirements of Taekwondo combat, evidence in Chapter 4.2 suggests that coaches may also need to consider strategies to assist the competitors' to effectively manage the stress responses in competition.

A 'psychophysical' training strategy is proposed to achieve this. This may include the use of 'psychological skills training' and/or the systematic exposure of the competitors' to the physical activity and the stress responses of fighting. Psychological skills training may be considered to alleviate competition state anxiety (cognitive and somatic elements) and the negative emotions associated with the stress response (Chapman *et al.,* 1997; Pieter and Heijmans, 2000). To this end, coaches and psychologists could consider implementing a range of cognitive and behavioural strategies including imagery, goal setting, relaxation, self-talk, concentration (attentional focus) and competition simulations into regular training practices (Gould & Maynard, 2009). These strategies should be implemented in a periodised fashion that complements the physical, technical and tactical preparations (Blumenstein et al., 2005). They should also be integrated using a standard 'education, acquisition and practice' phase framework (Blumenstein et al., 2005). It is, however, beyond the scope of the current thesis to prescribe specific cognitive and behavioural interventions to assist competitors' to reduce the negative emotions associated with competition.

It may be possible, however, to propose specific 'psychophysical' training strategies to prepare competitors' for the combined demands of the physical activity and the stress responses during championship events. The systematic exposure of an individual to a particular stressful situation (e.g. physical activity of the combat and the stress response to the fighting situation) may result in a 'habituation' response to the stress of that particular environment (Gerra *et al*., 2001; Grissom & Bhatnagar, 2009). The term 'habituation' in the field of stress neurobiology refers to a reduction in the physiological responses by an nth exposure to a repeated homotypic (same) stressor in comparison to the large responses elicited by acute exposure to that stressor (Grissom & Bhatnagar, 2009). To achieve this 'habituation' response, coaches should therefore consider modes of exercise that closely replicate the physical activity and the high stress hormonal responses elicited in Taekwondo competition. Two main exercise modes that may be recommended to satisfy these requirements include championship competition itself and the use of 'test match events'. Both of these exercise modes, structured in the right way, have the potential to evoke suitable activity profiles (physical workload) and stress hormonal responses for 'habituation' purposes (Chapters 4.2 & 5.1).

During the 'specific preparation' and 'competition' phases of a periodised programme, coaches should arrange for competitors' to compete in both championship and 'test match' competition events (e.g. Chapter 5.1). Competing in championship events may be ecologically favourable for 'stress habituation,' but its use is restricted to set periods within the annual 'competition calendar' that may not coincide with 'peaking' for certain events. Taekwondo test match events may therefore serve as more versatile model to prepare competitors for the physical activity and the stress responses in championship events. During the test match events, each competitor should compete in four to six full-contact combats during a single day (irrespective of the outcome of each combat) and these should be interspersed with varied recovery intervals. Coaches are advised to schedule these combats against high-level unfamiliar exponents in the presence of a large volume of peers and coaches (Chapter 5.1). To maximise authenticity, each match should be governed by an official international referee, scored according WTF regulations, and the score should be publicised. This fundamental test match strategy should maximise the psychophysical demands on the competitors' during each combat (Chapter 5.1). Coaches and practitioners are advised to monitor the competitors' psychophysical responses during the test match events with the use of physiological (e.g. HR, blood lactate, cortisol) and psychological (e.g. State-Trait Anxiety Inventory [STAI-2], Competition-State Anxiety Inventory (CSAI-2), Profile of Mood States [POMS] Inventory) measurements. This may provide useful information regarding the test matches suitably to elicit the 'stress response' and it may be used to monitor the efficacy of the 'habituation' responses.

The ability to provide accurate recommendations concerning the typical frequency and duration of sessions needed to safely habituate competitors' to the stress of Taekwondo competition is a little more problematic due to the limited available literature in this area. Most of the available research has been performed using animal models and the few studies that have examined the habituation responses to stress in humans are restricted to laboratory-based investigations. As such, the generalisabilty of this information to Taekwondo competition is unknown. Irrespective of these limitations, research from animal and human models suggests that: 1) repeated application of a stimulus (e.g. stress) results in a decreased response to that stimulus (habituation); 2) if the stimulus is withdrawn, the response tends to recover over time (spontaneous recovery); and 3) if repeated series of habituation training and spontaneous recovery are given, habituation becomes successively more rapid (potentiation of habituation) (Grissom & Bhatnagar, 2009). This suggests that habituation to stress may be developed and regressed in a similar fashion to other trainable characteristics (e.g. physiological adaptations).

It is not possible to provide accurate recommendations on the optimum dose needed to habituate individuals to the stress of combat, but evidence from human studies may act as a basic framework to structure test matches in Taekwondo. In humans, stress habituation has been documented eight days following a single exposure to a laboratory stress session (Gerra *et al*., 2001). Similar results have also been observed by performing one laboratory stress session per week for three weeks (Wust *et al*., 2005). A separate study has also identified stress habituation while performing one laboratory stress session every four weeks (3 sessions in total) (Schommer *et al*., 2003). In support of these human studies, investigations using animal models demonstrate that stress habituation may be maintained for up to three weeks after cessation of exposure (Grissom & Bhatnagar, 2009). These data may be used as a basic framework to inform stress habituation sessions in Taekwondo. On this basis, coaches might be advised to consider implementing 1 to 3 test match events in the ‘specific preparation’ and/or ‘competition’ phases of a periodised plan leading up to a championship event. For example, this may include one test match per week for three weeks or one test match every two weeks over a six week period. Coaches might be advised to ensure that these test match preparations are complete at least two weeks prior to championship competition (e.g. before starting the taper). The high injury risk associated with test match events may also be an important factor that governs the organisation of these practices leading up to a championship event. It’s worth bearing in mind at this point that there may be large inter-individual variation in the competitors’ responsiveness to stress habituation (e.g. high and low responders) (Grissom & Bhatnagar, 2009). Coaches are, however, strongly advised against subjecting competitors’ to high stress responses for intensive and sustained periods during a periodised programme. Such practices may cause serious harm to competitors’ such as SAM and HPA axis maladaptation and even burn-out. As such, the author strongly advises that further research into the efficacy and safety of such practices is performed *a priori* to being implemented into practice settings.

Strategies to Facilitate Recovery and Energy Availability between Successive Combats

The findings of Chapter 5.1 may also serve as useful framework to inform competition preparations and the selection of recovery interventions during a championship event. An important finding of Chapter 5.1 was that the recovery processes (as reflected by elevations in resting HR, NEFA, glycerol and lactate) were often incomplete between a number of the repeated combats. This response seemed to be more pronounced following short recovery intervals (e.g. 31 minutes). As such, coaches may wish to consider the use of interventions to reduce the recovery requirements of each combat and/or facilitate the recovery processes between combats in championship events.

Changes in blood and muscle metabolites such as reduced pH and increased lactate and H^+ may impair the contractile properties of the muscle during exercise (Juel, 1996). As such, strategies that promote faster return of these ‘unfavourable’ metabolites to baseline levels between the combats may be advantageous during championship events. One strategy that may be considered to facilitate the removal of these blood and muscle metabolites and restore the contractile properties of the muscle is active recovery (light intensity exercise) (Sairyo *et al*., 1993). Exercise performed at intensities between 30 and 45% of $\dot{V}O_{2max}$ (32% of $\dot{V}O_{2max}$ is proposed as optimal) in both continuous and intermittent formats significantly enhances the removal of these muscle and blood metabolites compared with passive recovery (Dodd *et al*., 1984). Such adjustments are usually detectable between 10 and 40 minutes into the recovery period (Dodd et al., 1984; Fairchild *et al*., 2003). On this basis, coaches should consider the use of active recovery when shorter rest intervals are anticipated between the combats (e.g. 15 to 30 minutes). To prevent this strategy from having a negative impact on the rate of PCr re-synthesis during the first 10 minutes of recovery, intermittent exercise modes are recommended (McAinch *et al*., 2004). An intermittent approach may also complement the use of nutritional interventions (e.g. use of recovery drinks) and prevent substantial glycogen depletion in type I muscle fibres (Fairchild *et al*., 2003). Actions such as jogging, walking and possibly low-intensity Taekwondo activities may be used. These should be performed at intensities of ~ 32 % of competitors' $\dot{V}O_{2max}$ for short durations interspersed with comparable rest intervals. For example, work intervals ranging between 1 and 3 minutes interspersed with similar rest periods should be considered (e.g. work:rest intervals of 1:1 or 1:2). In instances where longer recovery intervals between the combats are anticipated (e.g. > 30 minutes), passive recovery is advised to prevent substantial glycogen depletion in type I muscle fibres (Fairchild *et al*., 2003).

Strategies that aim to attenuate the production of these metabolites (e.g. the increase in muscle lactate and H^+ and the reduction in pH) during combat may also be favourable. This may reduce the recovery requirements of each combat and/or facilitate energy availability during the combats. Approaches that may be used to accomplish this include 'lactate tolerance' training (discussed earlier this chapter) and/or the use of nutritional interventions such as sodium bicarbonate and beta-alanine.

Supplementing with exogenous sodium bicarbonate ($NaHCO_3$) provides an electrochemical gradient between the intra- and extracellular milieu, allowing for greater proton (H^+) and lactate removal during intense exercise (Siegler *et al*. 2008). Providing enhanced extracellular proton (H^+) buffering using $NaHCO_3$ may therefore aid homeostatic maintenance of glycolysis for longer periods during competition and/or attenuate acid-base perturbations between the combats (Siegler and Hirscher 2010; Siegler *et al*. 2008). Oral ingestion of 0.3 $g/kg^{-1}.bw^{-1}$ of $NaHCO_3$ 1 to 2 hours prior to exercise typically increases muscle buffering capacity and improves performance in numerous high-intensity exercise settings (McNaughton, Siegler & Midgley, 2008). In fact, this strategy has been shown to enhance muscle buffering capacity and performance in simulated boxing and judo competitions (Artioli et al., 2007; Siegler and Hirscher 2010). In agreement with these investigations, Taekwondo competitors' could consider supplementing with 0.3 $g/kg^{-1}.bw^{-1}$ of $NaHCO_3$ 1 to 2 hours prior to the first combat of the championship event. It is pertinent to note, however, that such buffers can cause gastrointestinal upset and may not be tolerated well by all athletes. As such, competitors' are advised to test their responsiveness to different $NaHCO_3$ ingestion protocols during training before using this strategy in competition.

An alternative strategy that may be considered to exert comparable muscle buffering effects includes chronic supplementation with the non-essential amino acid beta-alanine. Oral supplementation with beta-alanine may facilitate muscle buffering capacity and exercise performance through increasing muscle carnosine concentrations (Artioli *et al*., 2010). Carnosine plays an important physiological role in the maintenance of acid-base homeostasis during exercise (Derave *et al*., 2010). Daily doses of 4.8–6.4 g of beta-alanine have been shown to elevate human muscle carnosine content by 60% in 4 weeks and 80% in 10 weeks resulting in enhanced buffering capacity and increased high-intensity exercise performance (Artioli *et al*., 2010; Derave *et al*., 2010). On this basis, Taekwondo competitors' could consider supplementing with beta-alanine in the weeks leading up to a major championship event. Once again, this strategy may have the potential to facilitate homeostatic maintenance of glycolysis for longer periods during competition and/or attenuate acid-base perturbations between the combats. Daily ingestion of 4.8-6.4 g of beta-alanine for 4 to 10 weeks leading up to a major Taekwondo championship event might be advised to enhance muscle buffering capacity. In a number of individuals, the acute ingestion of a high (single) dose of beta-alanine may evoke paraesthesia (e.g. mild tingling/pricking sensation on the skin). To minimise the incidence of paraesthesia, the use of small frequent doses (0.8 to 1 g servings every 2 to 3 hours) are recommended to achieve the total daily recommendations of 4.8-6.4 g (Derave *et al*., 2010).

Two alternative nutritional strategies that may facilitate energy availability and recovery between the repeated combats include creatine supplementation and carbohydrate intake. As the findings of Chapter 5.1 do not provide any information concerning the magnitude of the muscle PCr and glycogen use during combat and/or the extent of the recovery of these parameters between the combats the potential benefits will be highlighted briefly in this section. Oral creatine supplementation may enhance the PCr content of the muscles by up to 20% (Bogdanis *et al*., 2007). Increased PCr availability may permit higher ATP resynthesis from PCr for longer during intense exercise, act to buffer pH changes brought about by increased acidosis and promote faster PCr resynthesis during recovery (Bemben & Lamont, 2005). On this basis, Taekwondo competitors could consider supplementing with creatine leading up to a major championship event. The most common creatine loading scheme is 20 g/day (four doses of 5 g each) for 5-7 days followed by a maintenance load of 2-5 g/day for several weeks (Bemben & Lamont, 2005). Another common strategy that avoids an initial loading phase comprises creatine supplementation of 2-3 g/day for 4 weeks, which is typically maintained for 4 to 16 weeks (Bemben & Lamont, 2005). Both strategies are equally effective in raising muscle PCr content and in turn promoting ergogenic benefits (Bogdanis *et al*., 2007). As such, any of these creatine loading schemes could be considered by Taekwondo competitors' leading up to a major competition event.

The consumption of carbohydrates in the intervals between successive combats may facilitate muscle and liver glycogen resynthesis (Van Hall, Shirreffs & Calbet, 2000). Although muscle glycogen stores may not be completely restored during the rest intervals, carbohydrate intake that enhances glycogen resynthesis may be important to facilitate energy availability during successive combats (the importance of this strategy is clearly dependent on the initial muscle glycogen content and the magnitude of the glycogen depletion during the event). This strategy may be particularly suitable when more lengthy rest intervals are anticipated between the combats (e.g. 1 to 3 ½ hours) (Chapter 5.1) (Van Hall *et al*., 2000). The rate of glycogen resynthesis may be influenced by a number of factors including the timing of carbohydrate intake, the rate of ingestion and the type of carbohydrate consumed (Millard-Stafford *et al*., 2008; Burke *et al*., 2011). Glycogen resynthesis rates are higher when carbohydrate is ingested immediately post exercise (5-6 mmol/kg $w.w^{-1}./h^{-1}$) compared with a delay of 2 hours post exercise (3-4 mmol/kg $w.w^{-1}./h^{-1}$) (Ivy *et al*., 1988). In addition, carbohydrate ingestion rates of 1 to 1.2 $g.kg^{-1}.hr^{-1}$ have been shown to 'optimise' muscle glycogen synthesis rates within the first 4 hours compared with lower ingestion rates (e.g. 0.4 to 0.8 $g.kg^{-1}.hr^{-1}$) (Ivy *et al*., 1988). High to moderate glycemic index (GI) carbohydrates also facilitate higher glycogen resynthesis rates compared with low GI carbohydrates (Burke *et al*., 2011). On this basis, Taekwondo competitors might be advised to ingest high to moderate GI carbohydrates immediately following combats (at ingestion rates of 1.2 $g.kg^{-1}.hr^{-1}$) when 1 to 3 ½ hours are expected between the combats. This rate of carbohydrate intake could be sustained with either liquid or non-liquid forms using regular ingestion intervals (Millard-Stafford *et al*., 2008; Burke *et al*., 2011).

In summary, a range of competition-specific training strategies have been proposed to prepare Taekwondo competitors' for the multifactorial demands of championship events. The range of strategies recommended to prepare competitors' for the physical activity and the physiological demands of championship combats may be used to directly inform the structure of conventional Taekwondo practices. While a number of strategies have also been proposed to assist competitors' to effectively manage the stress responses in competition and to facilitate recovery and energy availability between successive combats, further research into the efficacy of such approaches is clearly warranted. Further research into the safety of 'psychophysical' training strategies in Taekwondo is strongly advised before being implemented into practice settings.

6.2.3 Research Implications

The findings contained within this thesis also have implications for studying the demands of Taekwondo. These findings may, therefore, be integrated into a 'Taekwondo research framework' to guide future investigations into the physiological demands of this combat sport (Figure 6.2.2) (Drust *et al.*, 2007). This section attempts to contextualise the research approaches available to study the demands of Taekwondo on the basic-applied research continuum (Atkinson & Nevill, 2001; Drust *et al.*, 2007), and provide a critical appraisal of the logistics associated with each technique and the data that is generated.

Research into the physiological demands of a sport can be placed onto a continuum from 'basic' to 'applied' in nature (Atkinson & Nevill, 2001; Drust *et al.*, 2007). The distinction between basic and applied research is important in determining the type of knowledge that is generated and the impact that the information may have for Taekwondo performance (Drust *et al.*, 2007). Basic research is designed to substantiate or discount theories of the underlying mechanisms that govern a particular phenomenon. This approach is usually adopted in the modelling of physiological mechanisms and involves the classical hypothetico-deductive method, null-hypothesis testing and the inclusion of sound/controlled experimental designs (Atkinson & Nevill, 2001). In contrast, applied research is concerned with examining factors that affect variables in realistic (externally valid) settings. In applied research, investigators may be interested in evaluating if a particular variable, irrespective of the mechanistic action, influences another in the 'real' world (Drust *et al.*, 2007). A close association exists between the basic-applied research continuum and the internal-external validity continuum (Thomas & Nelson, 2001). In basic research, the need to provide close control of key experimental variables (internal validity) may reduce the external validity of the findings. Conversely, the high external validity requirements of applied research may have a negative impact on internal validity in that there may be less control over extraneous variables.

The methods available to study the physiological demands of a sport such as Taekwondo include behavioural observations during competition, physiological evaluations in actual and simulated competition, and the assessment of competitors physical capabilities (Bangsbo, 1994; Drust *et al.*, 2007). In a research context, information concerning the physical capabilities of elite competitors may be used to indirectly determine the physiological demands of specific sports (Bangsbo, 1994). This notion is based upon the assumption that elite athletes have adapted to the regular physiological requirements of competition (Bangsbo, 1994). This rationale is relatively simplistic though, as performance on such tests may reflect competitors genetic endowment, health status and the demands of regular training practices as opposed to the less frequent physiological stress of Taekwondo competition (Toskovic *et al.*, 2004; Mohr *et al.*, 2007; Lippi *et al.*, 2009). The lack of specificity of the physiological testing methods to the actions of Taekwondo in these investigations (Thompson & Vinueza, 1991; Heller *et al.*, 1998; Toskovic *et al.*, 2004; Markovic *et al.*, 2005; Bouhlel *et al.*, 2006) raises further concerns surrounding the usefulness of this physical capacity information as an analogue of the demands of competition. The low external validity associated with this basic research framework (Figure 6.2.2) would suggest that the data obtained from such approaches may not accurately represent the demands of this combat sport.

Collecting physiological measures in authentic competition and training environments constitutes the most 'externally valid' approach to study the demands of competitive Taekwondo (Chapters 3.1, 3.3 & 4.2). This experimental approach is situated towards the applied end of the basic-applied research continuum (Figure 6.2.2). There are, however, a number of constraints associated with adopting this framework in training and competition. In conventional Taekwondo training settings, the synchronous practice of the activities by the athletes may preclude the efficient collection of a number of physiological measures such as blood samples and $\dot{V}O_2$ (Chapter 3.3). The physiological measures that can be collected in competition, on the other hand, may be restricted by the rules and regulations of the event, and the competitors' desire to engage in invasive procedures. The latter issue is particularly prevalent when the match outcome has significant implications for the athlete (e.g. Chapters 3.1 & 4.2). The high external validity of this setting may also compromise the degree of experimental control (internal validity) required to effectively study particular interventions. As such, this experimental framework may be better suited to investigations that attempt to quantify the fundamental physiological demands of combat as opposed to the study of interventions that necessitate high levels experimental control. It may be possible to collect basic 'field-based' measures such as HR with relative ease in Taekwondo competition (Chapters 3.1 & 4.2) (Heller *et al.*, 1998; Chiodo *et al.*, 2009). The collection of more invasive physiological measures in actual competition events such as blood sampling and muscle biopsy techniques may, however, require fastidious ethical considerations and appropriate cooperation from the athletes, coaches and the organisers of the event (Chapter 4.2). Irrespective of these efforts, it is clear that some approaches are simply incongruous with the nature of this combat sport (e.g. $\dot{V}O_2$ measures).

A number of alternative experimental approaches may be implemented to circumvent the constraints associated with collecting physiological measures in actual competition. Making activity observations in actual competition using time-motion analysis may be a favourable applied research construct (Chapter 3.2) (Figure 6.2.2). The data obtained from this experimental framework can provide valuable information concerning the energetic requirements of the combat activity (Chapter 3.2). This performance analysis technique may serve as a useful model to examine the influence of a range competition factors on the physical activity requirements of combat

(Chapter 3.2). The information generated via this technique may also be valuable to assist researchers in the development and validation of Taekwondo-specific exercise protocols for the purposes of monitoring fitness status, providing more detailed examinations of the energetic requirements of the combat activity and for studying the influence of interventions (Chapter 4.2).

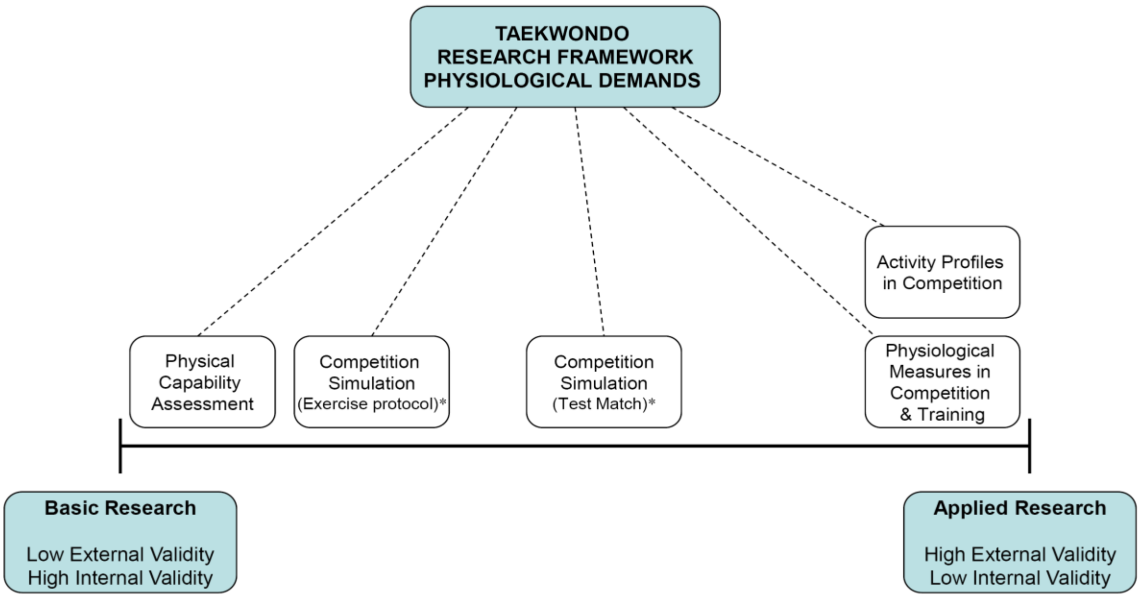
There are, however, a number of inherent complexities associated with adopting this experimental approach to study the activity requirements of Taekwondo combat. The objective and systematic recording and classification of the discrete activities involved in generating a comprehensive appraisal of the activity profiles in this combat sport (e.g. Chapter 3.2) is a relatively time consuming process. This is largely a consequence of the detail contained within the activity classification system, the high frequency of activity changes and the brief duration of each activity (Chapter 3.2). The time constraints associated with these procedures may influence a researchers desire to implement this strategy in future and therefore impact on the knowledge that is generated from this experimental approach. This issue may be particularly relevant to experimental designs that necessitate a large number of competitor evaluations. In these circumstances, it may be possible to exclude some elements of detail in favour of expediting the analysis process. The information that is generated does, however, need to contain sufficient detail to be meaningful (Chapter 3.2) (Drust *et al.*, 2007). The development of automated analysis/processing systems in Taekwondo may be a promising alternative to facilitate knowledge generation via this framework. Researchers should, however, be made aware of the importance of standardising these measurement procedures and the classification of activities as closely as possible. This will ensure suitable consistency across observations and it may facilitate the comparison of data between different investigations (Chapter 3.2) (Heller *et al.*, 1998; Matsushigue *et al.*, 2009). The efficacy of this applied research construct is also dependent upon a number of other design considerations. Consideration of the reliability (within-observer error) and the objectivity (between-observer error) of the activity classification system, and the inherent variability of the combat activity (within-competitor error) may be important for certain investigations (Drust *et al.*, 2007). Reliability, for instance, is an important consideration for investigations that are interested in examining whether the activity profiles differ between categorical variables (e.g. weight categories) or change over time (e.g. across the rounds and the matches) (Chapter 3.2). The detection of large within-competitor error, on the other hand, may necessitate a larger number of competitor observations to detect real systematic changes in a number of performance characteristics (Weston, Drust, Atkinson & Gregson, 2011).

An alternative experimental framework that may be adopted by researchers to overcome the constraints associated with collecting physiological measures in Taekwondo competition involves the development and use of competition simulations. There are two main 'simulation models' that may be considered in this endeavour. The first, involves the development of an 'exercise protocol' that simulates the activity pattern and the physiological responses of competition with the added benefit of providing close control over key experimental variables (Chapter 4.1) (Figure 6.2.2). In a number of intermittent sports, this simulation model provides an effective compromise between both external and internal validity in that it effectively replicates the energetic requirements of the tournament activity while providing close control over the environment (Drust *et al.*, 2000; Nicholas *et al.*, 2000; Roberts *et al.*, 2010). The efficacy of this simulation model to study the demands of Taekwondo may, however, be criticised on the grounds of external validity (Chapter 4.1). While it is possible for researchers to devise an exercise protocol that closely replicates the activity pattern performed in Taekwondo combat and to provide suitable control over key experimental variables, this simulation model may not accurately re-create the physiological and stress hormonal responses of actual competition (Chapter 4.2). The lack of 'external validity' provided by this exercise protocol would suggest that this simulation model may have limited application in the study of the physiological demands of this combat sport (Figure 6.2.2).

An alternative simulation model that researchers may consider to enhance the external validity of the physiological and hormonal responses, involves the development and use of Taekwondo 'test match' events (see Chapter 5.1 for specific details). This test match configuration may improve the external validity of the physiological and stress hormonal responses in comparison to 'exercise protocol' simulation models at the expense of a reduction in the degree of experimental control provided over the environment (Chapter 5.1) (Figure 6.2.2). The degree of external validity provided by Taekwondo test match events may be evaluated by comparing the activity patterns and the physiological responses with those observed in championship events. While this simulation model may be associated with a reduced degree of experimental control in comparison to 'exercise protocol' based simulations, it may offer several advantages over collecting physiological measures in championship events. This simulation model may be favourable in situations where the use of invasive physiological techniques in competition are restricted by the rules and regulations of the event, and/or by a competitor's desire to engage in such procedures in vital matches. Test match events may also offer researchers' greater control of key experimental variables (e.g. the timing of the combats and blood sampling) than championship events, and thereby permit more detailed and effective examination of the energetic requirements of Taekwondo competition (e.g. Chapter 5.1). In a number of combat sports, this simulation model has been implemented into repeated measures research designs to examine the influence of specific interventions on the physiological and performance responses in combat (Franchini *et al.*, 2009; Artioli *et al.*, 2010). The efficacy of this model in this context is, however, dependent upon the variability (within-competitor error) of the activity patterns and the physiological responses in these test matches. This assessment should be made *a priori* to undertaking investigations of this nature.

In summary, a number of diverse approaches are available to researchers to study the physiological demands of Taekwondo. These varied approaches have, therefore, been integrated into a 'Taekwondo research framework' to guide future investigations into the physiological demands of competitive Taekwondo (Figure 6.2.2). This framework contextualises the available research approaches on the basic-applied research continuum. Researchers are encouraged to decide *a priori* where their research question lies on this basic-applied Taekwondo research continuum (Figure 6.2.2). This distinction is important as it may influence the type of research approach that is selected, and therefore the outcomes and conclusions that can be drawn from the results. A failure to acknowledge the importance of this distinction may lead to poorly designed research projects or even to conclusions and practical recommendations that are inaccurate and misleading. It is clear that an equal commitment to both basic and applied research is necessary to advance information concerning the physiological demands of Taekwondo. It is important to realise that there is no difference in the quality or intellectual rigour between basic and applied investigations, merely a difference in the type of research question (Atkinson & Nevill, 2001).

Figure 6.2.2: Taekwondo Research Framework



Notes: * The location of these competition simulations on the basic-applied research continuum is dependent upon both reliability and validity checks

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

The individual studies undertaken in this thesis have enabled the development of two distinct frameworks to guide the training process in Taekwondo and to inform future research into the physiological demands of this combat sport. During the research process, a number of further research questions have arisen, which have prompted the formulation of recommendations for future research.

Investigations into the fundamental physiological demands of Taekwondo in this thesis demonstrate that the intensities of conventional Taekwondo training practices, delivered by experienced international coaches, are often insufficient to prepare competitors for the cardiovascular demands of international competition (Chapters 3.1 & 3.3). Future research should attempt to establish whether this finding is a consequence of the inappropriateness of training to emulate the physical activity requirements of combat (Chapter 3.2) or the failure of these training practices (e.g. sparring) to incite the stress responses that are experienced in championship events (Chapter 4.2). This may have significant implications for the structure of training programmes.

An applied research framework was implemented to study the fundamental physiological demands of conventional Taekwondo training activities in this thesis (Chapter 3.3). While this approach optimised the external validity of the data, the synchronous practice of the activities by the athletes in this setting precluded the efficient collection of a number of physiological measures. The evaluation of additional physiological measures (e.g. $\dot{V}O_2$ and blood lactate) is necessary to provide a more comprehensive insight into the aerobic and anaerobic energetic requirements of these activities. The use of simulated conditioning sessions that replicate the activity profiles and the structure of conventional Taekwondo training practices may offer an effective compromise between external and internal research validity to permit the collection of additional physiological measures, and thereby advance our understanding of the physiological demands of these activity practices.

The use of time-motion analysis to determine the physical activity requirements of Taekwondo combat identified that conditioning sessions may need to be specialised to the requirements of specific weight categories (Chapter 3.2). Only three of the eight standard WTF weight categories were, however, selected for analysis in this thesis. Further research into the activity profiles of the remaining WTF weight categories is clearly necessary to tailor conditioning to the activity requirements of these specific weight divisions. There is evidence to suggest that the activity profile information contained in this thesis may not be generalisable to other combat styles and/or levels of competition (Chapter 3.2). Further research is, therefore, necessary before such strategies can be adopted for other styles of Taekwondo combat.

Time-motion analysis is an applied research construct that may be used to examine the influence of a range of competition factors on the physical activity requirements of Taekwondo combat (Chapter 3.2). The efficacy of this approach in certain experimental designs may, however, be dependent upon the degree of variability (within-competitor error) exhibited by the activity patterns. High within-competitor error, for instance, may necessitate a large number of competitor observations to detect real systematic changes in a number of performance characteristics (Weston *et al.*, 2011). Researchers are, therefore, encouraged to investigate the inherent variability of the activity patterns between Taekwondo combats.

Research in this thesis highlights the importance of preparing Taekwondo competitors to effectively manage the stress responses to fighting in addition to the physical activity requirements of combat (Chapter 4.2). The use of 'psychological skills training' and the systematic exposure of the competitors to the physical activity and stress responses of fighting have been proposed as potential strategies to assist Taekwondo competitors to effectively manage the stress responses in competition (Chapter 6.3.1). Future investigations should attempt to establish the efficacy of these approaches and other techniques in managing the stress responses in Taekwondo. A psychophysical research framework is recommended (e.g. the collection of psychological and stress hormonal measures) to determine the effectiveness of these techniques in managing the stress responses in this combat sport.

Research into the physiological demands of performing repeated Taekwondo combats in this thesis (Chapter 5.1) provides a number of important findings that serve as a framework to direct future research investigations. Firstly, the recovery processes were largely incomplete when short recovery intervals occurred between the repeated combats (Chapter 5.1). It may, therefore, be valuable for future investigations to examine the effectiveness of different strategies in facilitating the recovery processes between the combats. Secondly, the successive combats in this study resulted in reduced plasma noradrenaline and lactate responses to combat and increased HR responses earlier in combat. It was proposed that these responses could reflect a change in the activity of the competitors' and/or altered metabolic function in favour of an increased reliance on aerobic metabolism and diminished anaerobic energy yield. Future research should attempt to substantiate this proposition by using more invasive measurement techniques (e.g. muscle biopsy and gas exchange measurements).

6.4 CONCLUSIONS

The primary aim of this thesis was to examine the physiological demands of competitive Taekwondo. The objectives formulated in Chapter 1 were largely fulfilled and as a consequence the studies contained within this thesis collectively contribute original information concerning the physiological demands of Taekwondo. This was achieved by adopting a variety of research approaches including the collection of physiological measures in competition and training, the examination of the activity profiles in competition, and the development and use of competition simulations. The knowledge generated from these experimental approaches has enabled the development of two distinct frameworks. An ‘ergonomics model of Taekwondo training’ is proposed to guide the training process for the specific requirements of championship Taekwondo competition. This model allows training to be considered as interfacing with the physiological demands of competition and the psycho-physical capabilities of the competitors. Training that is structured according to the principles of this ergonomics model should serve to promote specific structural adaptations to optimise physiological function and performance in Taekwondo. A ‘Taekwondo research framework’ is also proposed to guide future investigations into the physiological demands of Taekwondo. This framework contextualises the research approaches available to study the demands of Taekwondo on the basic-applied research continuum. It is hoped that this framework will inform both the direction and methodology of future investigations to ensure that the knowledge generated is valuable to both the scientific and practitioner community.

CHAPTER 7

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